Examining construction productivity improvement by applying Takt Time Planning to generate an execution guideline

Master Thesis

International Master of Science in Construction and Real Estate Management

Joint Study Programme of Metropolia UAS and HTW Berlin

from

Jeton Gjolleshi

567938

Date:

Berlin, 27.10.2020

1st Supervisor: Prof. Dr. –Ing. Nicole Riediger

2nd Supervisor: Ing. Ammar Al-Saleh

[Acknowledgement]

I would like to express my gratitude to my family for their continuous support and the transmitted enthusiasm in completing this master thesis.

I wish to extend my special thanks to my supervisors, Prof. Dr. –Ing. Nicole Riediger and Ing. Ammar Al-Saleh, for their assistance and the consistently shared knowledge over Project Management and Lean Construction through this Master Programme, which inspired me to write this thesis.

I also want to thank my colleagues for their support and all the pieces of advice shared in the last two years.

Proposal/Research Plan

Topic: Examining Construction productivity improvement by applying Takt Time Planning to generate an execution guideline.

Student Name: Jeton Gjolleshi

Student Number: s0567938

Background

"Takt" is a German word which stands for the beat of music, rhythm or repetition time. Takt time planning (TTP) was initially used for organizing and manufacturing the Japanese aircraft industry during the second world war. The rhythm was used as the analogy of setting the pace and repetition cycle of different activities to simplify and increase the production rate so they would be synchronized to the demand for production. After the war, Toyota borrowed and developed this concept for it's Just in Time' production system (strategosinc.com, 2007).

Regarding the construction, this tool aims to align all the crews and create a flow on-site by reducing the time duration of each activity and optimizing and smoothing all the construction processes. However, Project Managers find it difficult to adapt TTP to construction sites without extensive plans. The idea of producing more in less time might require additional crews sometimes, thus the aim to create a steady production rate complicates.

Furthermore, construction seems to be the only industry that did not embrace the production increase over the past decades properly. A significant number of construction companies are using Lean Management methods to optimize the overall management process. Yet, there is not a definitive guideline on how to implement Takt Time planning in all the construction sites.

Takt is widely known as a tool to increase the production rate. Therefore, no precise economic evaluation is done to its impact related to general costs, and not a clear linkage with BIM tools is defined to create a synergy between BIM and Lean concepts.

Research Questions and Objectives:

This thesis will focus on both the advantages and disadvantages of implementing takt time in construction. The possibility to generate e Takt implementation plan guideline which can be universally used in construction industry.

This research will focus on:

1. How can TTP be generated and implemented? How does it impact the Master Schedule?
2. The impact of TTP on construction sites regarding time, quality, and cost. Pull and push strategy, the effects of Takt in the cash flow? Cost related result of Takt?
3. Buffer Management in TTP, comparative analysis.
4. Monitoring and Controlling in Takt projects, how to maintain and optimize the activities pace.
5. Evaluating the possibility of a Takt implementation guideline so other projects can benefit from its implementation.

Moreover, the result of this thesis will answer the following questions:

1. Identifying takt in construction projects.
2. How can the production rate be adjusted?
3. Which are the limitations of takt time?
4. How can architectural design affect this tool?
5. Which other tools can be combined with takt time to optimize productivity?

Research method and materials

To obtain the required objectives, the research will be organized into four dimensions:

1. Previous studies to identify the current research progress done on this tool.
2. Comparative case studies to obtain results, identify the limits, optimize the buffer, focus on the objectives.
3. Case study, applying TTP with BIM tools.
4. Different possible scenarios over the Takt Controlling projects and the role of subcontractors in the success of this tool.

First Supervisor Signature: 18.12.15

Second Supervisor Signature:

Abstract

This Master Thesis presents a detailed analysis of three existing case studies that apply Takt Time Planning to create a steady workflow in construction projects. These case studies introduce a structured approach to scheduling a fast plan and illustrate the productivity improvements when Takt Time Planning is used as a work structuring method. Aiming for a continuous flow in construction while eliminating all types of waste requires comprehensive coordination and clear organizational features to deal with all the constraints that the implementation process presents. Therefore, the focus of this thesis is to investigate different perspectives of integrating Takt Time Planning while demonstrating the efficacy of its structured implementation.

A guideline that helps with the implementation of this planning technique is generated, and it focuses on the improvement of the triple constraints of construction management: time, cost, and quality. Shortening the construction time while maintaining the quality and reducing costs requires incentive forms of motivation for all the participants to commit on the same scope. Therefore, the application of Takt Time Planning requires a new level of collaboration between all the involved actors during all the phases of construction. Moreover, it requires analyzing pre-conditions, which simplifies the process, innovative forms of assessing the schedule’s reliability, and utilization of different tools that add value to the implementation on the scheduling process.

Keywords: Takt Time Planning, productivity improvement, implementation guideline, location-based scheduling.

Table of Contents

Abstract ..... **VI**

Table of Contents ..... **VII**

Table of Figures ..... **X**

List of Tabulations ..... **XII**

List of Equations ..... **XIII**

List of Abbreviations ..... **XIV**

1. Introduction **1**

1.1 Research background and objectives 3

1.2 Research questions 4

1.3 Research boundaries 4

1.4 Research methodology 4

1.5 Thesis structure 5

2. Project Management **6**

2.1 Introduction 6

2.2 Traditional Construction Planning 7

2.3 Structuring 7

2.4 Scheduling 7

2.5 Cost Estimation 9

2.6 Resource Allocation 10

2.7 Monitoring and Controlling 11

2.8 Barriers to Traditional Planning 11

3. Lean Management **13**

3.1 Introduction 13

3.2 Toyota Production System 13

3.3 Theory of production in construction 15

3.4 Construction Lean Management ... 19

3.5 Work Structuring Method ... 21

4. Productivity improvement through Location-based Scheduling ... 23

4.1 Introduction ... 23

4.2 Line of Balance ... 23

4.3 Location-Based Management System ... 28

4.3.1 Planning phase ... 28

4.3.2 A case study using LBMS in the planning phase ... 29

4.3.3 Monitoring and Controlling ... 31

4.4 Point-to-point technique ... 33

5. Takt Time Planning ... 35

5.1 History of Takt Time Planning ... 35

5.2 Takt in industrial processes ... 36

5.3 Takt Time Planning in construction ... 38

5.3.1 Defining Takt in construction projects ... 38

5.3.2 Takt Schedule ... 42

5.3.3 Takt Control ... 43

5.4 Takt Time Planning as a work structuring method ... 44

5.5 Drafting a Takt Time Plan ... 46

5.6 Advantages of using Takt Time Planning ... 49

5.7 Complements with Last Planner System™ ... 50

5.7.1 Last Planner System ... 51

5.8 Complements with Location-Based Management System ... 53

5.9 Complements with Building Information Modelling ... 54

6. Case Studies ... 58

6.1 Bergen Academy of Art & Design – KHiB ... 58

6.1.1 Introduction 58

6.1.2 Project timeline 59

6.1.3 BIM model and procurement 60

6.1.4 Takt-Time Plan 61

6.1.5 Analysis of the case study 67

6.2 Residential building in Finland 69

6.2.1 Introduction 69

6.2.2 Takt strategy 69

6.2.3 Takt control 71

6.2.4 Analysis of the case study 73

6.3 Anderson Lucchetti Women's and Children's Center (WCC) 75

6.3.1 Introduction 75

6.3.2 Takt strategy 76

6.3.3 Analysis of the case study 80

7. The implementation guideline of Takt Time Planning in construction projects 82

7.1 Proposed Framework and Recommendations 85

7.2 Discussions 88

7.3 Research Questions Answers 90

8. Conclusions 95

8.1 Recommendations for future research 97

Declaration of Authorship 98

References 99

Table of Figures

Figure 1: 5 Stages of Project Management. 6
Figure 2: CPM diagram.. 8
Figure 3: Project Schedule developed in MS Project... 9
Figure 4: House of Toyota, TPS 14
Figure 5: Koskela's transformation process.. 16
Figure 6: Simplified scheme of creating the flow 17
Figure 7: Koskela's Value generating scheme.. 18
Figure 8: Lean Journey.. 20
Figure 9:The 4P in Lean Construction 21
Figure 10: Relation between the work chunks 22
Figure 11: Graphic illustration of the LOB.. 24
Figure 12: Illustration of waiting times between activities because of different production rates 26
Figure 13: Synchronized LOB... 27
Figure 14: Construction Schedule using LBMS in Vico Schedule Planner 30
Figure 15: LBMS schedule forecasting, using Vico Schedule Planner. 32
Figure 16: Point-to-point methodology.. 33
Figure 17: Shingo's two-way production system.. 37
Figure 18: The Parade of Trades... 38
Figure 19: Defining the Takt time for different activities of the same working package in different locations... 40
Figure 20: Takt-Time Plan 42
Figure 21: Triads of Lean Project Delivery System, LPDS 46
Figure 22: Takt time plan format... 47
Figure 23: Takt Time Plan, train visualization 48
Figure 24: Takt schedule for structural activities.. 48
Figure 25: Benefits of using TTP in construction 50
Figure 26: The Last Planner System, planning board.. 53
Figure 27: Comparison between push strategy (A) and pull strategy (B) 53
Figure 28: The usage of Lean and BIM to improve productivity............................... 55
Figure 29: The list of attributes that each component of the building should have ... 56
Figure 30: 4D Takt schedule for framework construction. 57

Figure 31: Detailing the BIM model and deliverable packages (wave 1,2,3) 60
Figure 32: 14-10-6-4-1 preparation meetings. 63
Figure 33: TTP of KHiB project 66
Figure 34: TTP for interior works of apartments 71
Figure 35: Takt zones and Takt time 77
Figure 36: Level of detail in TTP 78
Figure 37: Conceptual framework for TTP implementation guideline in construction projects. 87

List of Tabulations

Table 1: Resource Leveling and Smoothing 11
Table 2: Project descriptive data 59
Table 3: Lean Strategy timeline (2013-2016) 59

List of Equations

Equation 1: Activity duration equation 8
Equation 2: Cost estimation equation 9
Equation 3: Calculating the duration of one activity equation 24
Equation 4: Assessing the quantities in a period equation 25
Equation 5: Simplified equation for the duration of the activity in the LBMS method. 30
Equation 6: The equation for Takt production.. 37

List of Abbreviations

BIM - Building Information Modelling

BOQ - Bill of Quantities

CBS - Cost Breakdown Structure

CPM - Critical Path Method

GC - General Contractor

IFOA - Integrated Form of Agreement

IGLC - International Group of Lean Construction

JIT - Just-in-Time

KHiB - Bergen Academy of Art & Design

KPI - Key Performance Indicator

LBMS - Location-based Management System

LOB - Line of Balance

LPDS - Lean Project Delivery System

LPS - Last Planner System

OBS - Organizational Breakdown Structure

PM - Project Manager

PTP - Point-to-Point

SSU - Standard Space Unit

TFV - Transformation-Flow-Value

TPS - Toyota Production System

TPTC - Takt Plan Takt Control

TTP - Takt Time Planning

WBS - Work Breakdown Structure

WCC - Anderson Lucchetti Women's and Children's Center

WIP - Work-in-Progress

1. Introduction

Improvement of productivity is the main focus of the construction industry over the last forty years (Aziz and Hafez, 2013). The Critical Path Method (CPM) is the most common scheduling technique used in construction. CPM estimates the most extent possible duration of the construction project and visualizes the so-called critical tasks which compromise the length of the project when not executed within the pre-set timeframe (Lu Ming and Li Heng, 2003). However, the CPM fails to visualize different aspects of planning, such as location and the waiting times between the subprocesses of the main task, which often causes delays and requires the usage of extensive means and methods that might result in additional costs (Koskela et al., 2002).

(Sacks and Partouche, 2010), on their research over the construction of the Empire State Building in 1931, raise the question if the same building could be built at the same pace (14 months) nowadays. For this project, the location of the activities and the vertical degree of repetitiveness factor successfully accelerated the construction duration. The Line-of-balance technique was used as a scheduling methodology for this purpose. Nowadays, the development of the Lean production system, which is developed based on the means and methods of Toyota Production System (TPS), enhances the productivity of construction sites (Sacks et al., 2010).

Based on the TPS principles developed by Engineer Ohno (1988), Lauri Koskela (1992) developed the Transformation-Flow-Value theory, which built the foundations for the new approaches in delivering construction projects. According to Koskela, enhancing the productivity of the construction processes requires designing a continuous workflow of the production system, controlling measures using different means and methods depending on the specific process. Lastly, the learning experience during the implementation should improve the production system continuously (Koskela, 1992).

Takt Time Planning (TTP) is a Lean scheduling technique that aims to create a continuous workflow in the construction processes in order to improve the efficiency of the production system (Frandson et al., 2013). TTP is a location-based schedule, which consists of designing a synchronized production system by leveling the duration of all the activities and efficient resource utilization through all the construction processes. The period of implementing a task is known as Takt.

As a concept emerged from the Toyota Production System, the Takt production should meet the expected demand rate. In order to meet the demand rate, a balanced production system is planned, working areas are clearly defined, available resources are assigned, buffers are eliminated, and a disciplined movement of the working crews is designed. The movement of trades was first introduced by Tommelein (1999), and it displays the exact location on where and when each trade will perform. Its combination with the equal duration of the tasks results in a continuous workflow production system in which clashes and waiting times between different working trades are eliminated.

In a Takt plan, all the tasks are of equal importance. Eliminating the buffers between the activities and minimizing the inventory capacities of the sites as the locations are designed for the performing crews tightens the flexibility borders of TTP. Therefore, an adequate supply chain and optimized implementation logistics are required. Moreover, the amount of information needed for delivering the work in the required quality is considerably high. Hence, the usage of additional tools that add value to TTP and facilitate the whole process is required. Also, the comprehensive collaboration achieved through the Last Planner System enhances the commitment of the crews to the schedule. Nevertheless, a reliable TTP also requires a realistic design approach.

In construction projects, TTP is mainly used to improve the productivity of repetitive activities. However, in construction, all the operations have a repetitiveness coefficient, classified as horizontal and vertical development. The challenge of designing the production system using TTP as a work structuring method, depends on combining the repetitiveness factor with the corresponding location. There are numerous projects which have applied TTP as a work structuring method, where significant time improvements were achieved.

This thesis explores different components of TTP and presents a guideline Framework for the implementation of TTP from the early stage of Project Definition. The guideline includes the aspects which should be taken into consideration, the pre-conditions of using TTP, and recommendations for a successful implementation.

1.1 Research background and objectives

Takt Time Planning aims to create a continuous production workflow to meet the actual demand. Iris D. Tommelein (2017) categorizes TTP as a process that is done between the Master Schedule and the lookahead process of the Last Planner System. Tommelein and Frandson (2014) presented the five stages of developing a TTP, based on which Adam Frandson (2019), in his dissertation, proposed TTP as a work structuring method, listing the requirements of a Takt production system and the steps to achieve a continuous workflow.

A theoretical framework for TTP is presented by Binninger et al. (2017), which consists of eleven steps. However, this framework focuses more on the crew aligning to achieve the on-site synchronization in terms of time and place to produce a balanced plan. (Dlouhy et al., 2017) presented Takt planning as e three-level method as a new approach of Takt implementation. The aim was a standardization between the three proposed processes, which could be used for other projects.

All the proposed implementation frameworks focus more on the TTP generation, and less research is done regarding the pre-preparations, different phases of implementing specific participants, stakeholder’s responsibilities and expectations, training, and additional tools used in a successful planning process. Frandson’s (2019) work structure method at task level proposal gives to TTP a broader perspective. However, in this research, the main focus is on TTP implementation in non-repetitive interior works, and the author assumed that the collaboration between the trades and all the required coordination was achieved.

This thesis will focus more on the perspectives offered by Frandson and will aim the creation of a clear linkage of TTP between the project design phase and implementation phase, focusing more on the collaborative aspect and the preparations before drafting the plan. This process consists of the stage between Project Definition and Lean Design in the triads of the Lean Project Delivery System (LPDS) introduced by Ballard (1999). Moreover, this thesis aims to draw a theoretical framework for TTP, including the participants, logistics, and implementing conditions at different stages.

In addition, the focus will also be on the quality of delivering a project using TTP as a work structuring method, including different problems and solutions, and different preparative tools that aim to produce a zero-defect production system.

1.2 Research questions

The main derived research question are:

- How can TTP be generated and implemented? How does it impact the Master Schedule?
- The impact of TTP on construction sites regarding time, quality, and cost. How does the pull and push strategy effects the Takt's cash flow? What are the cost related results of Takt implementation?
- How to manage the buffer in TTP?
- Monitoring and Controlling in Takt projects, how to maintain and optimize the activities pace?
- Is it possible to generate a Takt implementation guideline that can be applied universally in construction projects?

1.3 Research boundaries

This thesis analyzes the implementation of TTP in three different projects. The theoretical boundaries of this research, therefore, are conditioned by this analysis, which limits to quantify individual trades improvement. The overall implementation performance is quantified by the available data of these case studies. Moreover, costs related to TTP implementation are not captured accurately, because many companies consider the financial data as confidential information. As a result, the recommendations of how to implement the TTP in construction projects will assume the overall project production efficiency.

1.4 Research methodology

In order to achieve the research's objectives, an in-depth literature review regarding TTP was conducted. The research has been developed based on the outcome of a wide range of articles, journals, books, and documentaries about TTP implementation and its relation with other Lean concepts. The conference papers regarding TTP published by the International Group of Lean Construction (IGLC) were analyzed to structure this research, evaluate, and categorize the available content.

The analysis of existing case studies is conducted to identify the potential phases on which TTP can be broken down. The case studies have undergone the principle of including all types of construction works and phases. This thesis filtered the crucial available options. A combination of the phases of Takt implementation and the participants in each phase in order to understand their responsibilities and the effect that each one has on the outcome of the TTP is part of this research. The role of additional tools and technologies, and the linkage of procurement and supply chain, is analyzed to define theoretical approaches for the incorporation of TTP into the construction projects.

1.5 Thesis structure

Chapter 1 introduces the research by giving an overview of the current status and identifying the gap. The research methodology, scope, and objectives are also outlined.

Chapter 2 describes all the aspects of project management and introduces the terminologies of the traditional approach.

Chapter 3 presents the Lean Management in construction foundations and outlines the differences with the traditional project management. Moreover, new concepts of continuous flow and adding value principles are covered in this chapter.

Chapter 4 introduces the location-based scheduling tools and identifies respective implementation frameworks to find similarities with Takt Time Planning.

Chapter 5 describes Takt Time Planning, presents all the perspectives of this scheduling technique, and reviews complementary tools which, combined with Takt Time Planning, add continuous value to the construction projects.

Chapter 6 presents three case studies that use TTP as a structured approach since the early stages of the project.

Chapter 7 proposes the implementation guideline, identifies its boundaries, and answers the research questions.

Chapter 8 concludes the thesis.

2. Project Management

In this section, different aspects of construction planning, based on previous research, will be discussed. The main focus will be on the phases of construction projects, used techniques and available tools, and the managerial challenges. Moreover, the role of the Project Manager (PM) and other project participants will be defined in different stages of the project.

2.1 Introduction

Project management encompasses all the coordination, planning, and controlling from the beginning of a project to fulfill the client requirements. In other words, the project manager ensures the project completion would be within the budget, on time, and the required quality according to client objectives. PMBOK divides the project management process into five stages, as illustrated in the figure below:

Figure 1: 5 Stages of Project Management.

In this process, the Planning phase determines the total scope and considers all the activities and measurements to achieve the objectives and complete the stage (PMI, 2017). Execution of the whole project is not always a matter of planning. Instead, it considers implementing certain activities or achieving a milestone (Klein, 2000). (Hendrickson and Au, 2008, 1998) describes the construction planning as follow:

"The choice of technology, the definition of work tasks, the estimation of the required resources and durations for individual tasks, and the identification of any interactions among the different work tasks."

Planning is one of the critical PM responsibilities to coordinate and control the project by presenting efficient solutions, which enhance the quality of the performance. Planning can be done during different project stages, like design, pre-construction, construction, etc. Nevertheless, early planning is conducted by the PM and aims to optimize the cost, time, and scope efficiently (Kerzner, 2003).

2.2 Traditional Construction Planning

Construction planning consists of various general processes, which need to be practiced and implemented by PM and followed by stakeholders (NEALE and NEALE, 1989).

2.3 Structuring

The scope of a project would become more tangible and manageable when splitting it into the essential deliverables. It is the PM duty to have a comprehensive understanding of the project in order to identify the core works and break them into detailed jobs. This technique is known as Work Breakdown Structure (WBS), which categorizes the project into a hierarchical work structure (Burghate, 2018). According to the author, each level of work needs to be broken down into manageable activities. This is done by ensuring that the determined activities can accomplish the objectives. This tool helps PM recognize precedence relationships between the works to generate activities sequences (Klein, 2000).

The other structure that needs to be identified in the planning process is the stakeholders that will deliver the works. This structure is called Organization Breakdown Structure (OCS), which, like WBS, contains the level of hierarchies of the organization aspect. OBS presents the project organization's efficiency based on the ability of involvements to reach the project objectives. A clear organizational chart is critical for illustrating the participants' responsibilities in the project, and eventually, it affects the successful implementation of the project.

Costs, like work and organization, need to be decomposed in order to estimate the cost of the project. Cost Breakdown Structure (CBS) contains the price of all the building components, detail of construction activities, and resource costs. CBS needs to be transparent to understand what is included in the structure (Kerzner, 2003; Kischk et al., 2002).

2.4 Scheduling

Scheduling is the outcome of the structuring process when all the works, organization, and costs are defined (Callahan et al., 1992). Scheduling focuses on the time duration of a project. In a schedule, the time boundaries of activities are determined by respecting the activities' interdisciplinary relationships. Activity duration is calculated mostly by the following equation:

$$Duration\ (d) = \frac{Quantity * (Manpower - \frac{h}{unit})}{8\frac{h}{d} * (Number\ of\ labor\ in\ crew)}$$

Equation 1: Activity duration equation. (Callahan et al., 1992)

One of the most common scheduling techniques in construction is the **Critical Path Method (CPM)**. CPM is a diagram network to determine the project's duration by capturing critical activities and their duration. Critical activities refer to the events that need to be done on time and delay from critical activities move on the completion date of the project. A well-defined WBS and calculating the duration of each activity are essential in this method (NEALE and NEALE, 1989). Figure 2 illustrates a CPM diagram that each circle represents an event with its duration where arrows define the dependencies between activities, and red arrows show the project's critical path. C, E, F, G, H are the critical activities.

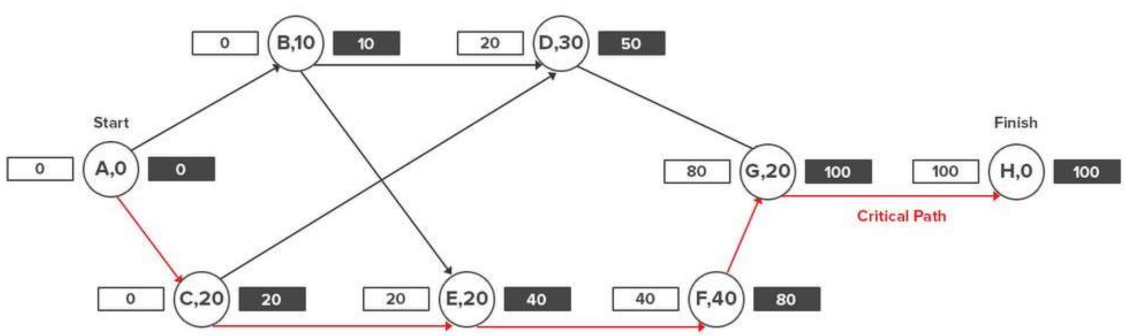


Figure 2: CPM diagram. (Cohen, 2018)

Bar chart (Gantt chart) is the other standard tool of scheduling, where the WBS activities are listed on the left side, and the duration of each event can be found on the right side by a scaled-horizontal bar (Mubarak, 2010). Gantt chart is one of the most popular PM tools because of its graphical presentation, simplicity, easily comprehended, and by linking the activities, the dependencies can be recognized. Figure 3 displays a schedule by the Gantt chart in Microsoft Project software.

Task Name	Duration	Start	Finish	Predecessors	Resource Names
Execution Planning	**74 days**	**Mon 16-12-19**	**Thu 26-03-20**		
Receive approved plan	0 days	Mon 16-12-19	Mon 16-12-19		
Meeting b/w diff stakeholders	2 days	Mon 16-12-19	Tue 17-12-19	2	Coordination Meeting
Detailed Architectural Plan	20 days	Wed 18-12-19	Tue 14-01-20	3	Architect
Detailed MEP Planning	15 days	Wed 15-01-20	Tue 04-02-20	4	MEP Engineer
Detailed HVAC design	15 days	Wed 15-01-20	Tue 04-02-20	4	HVAC Engineer
Miscellaneous designs	15 days	Wed 15-01-20	Tue 04-02-20	4	Acoustic,Insulation,F
Review in Architectural plan according to MEP and HVAC	7 days	Wed 05-02-20	Thu 13-02-20	6,5,7	Architect, HVAC Engineer, MEP Engineer
Detailed Architecture Plan ready	0 days	Thu 13-02-20	Thu 13-02-20	8	Architect
Reviewing in structural	10 days	Fri 14-02-20	Thu 27-02-20	8	Structural Engineer,

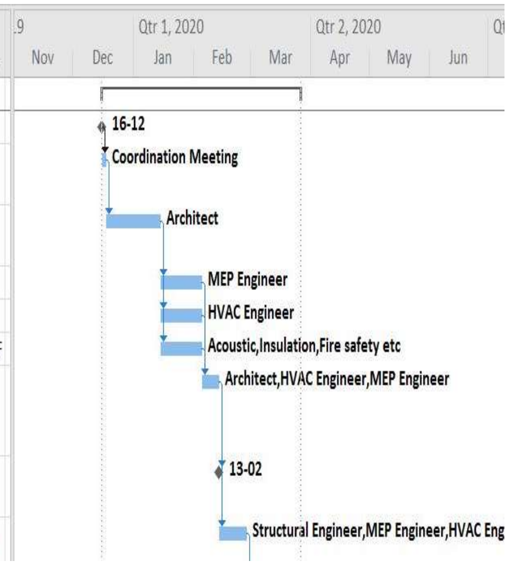


Figure 3: Project Schedule developed in MS Project.

The determination total and free float are also done on this stage after finding the critical path by CPM, bar chart, or calculation. Total float is the latest finish time of an activity minus the earliest start time, less the duration of the activity. Free float is determined by the earliest start of succeeding activity minus the earliest start of the desired activity minus the activity's total length(NEALE and NEALE, 1989).

2.5 Cost Estimation

Cost estimation during the planning process is based on the Bill of Quantity (BoQ) from the design phase, the allocated resource costs, and the productivity rates of the resources (Callahan et al., 1992). Accurate cost estimation is critical when it comes to using the cost/value comparison to monitor the progress of the project implementation. As presented in the equation below, the resources allocated, and all the associated costs will be calculated based on the quantities. This makes the BoQ a fundamental component in the planning phase.

$$Total\ Cost = \Sigma\ Q * (M + E_M + W * L)$$

Equation 2: Cost estimation equation. (Callahan et al., 1992)

Where:

Q = Quantity of the project element

M = Cost of the materials

E_M = Cost for the machinery

W = Human resource cost/h

L = Productivity rate

2.6 Resource Allocation

Planning cannot be efficient without allocating the resources, which refer to the available workforce, machine, money, and materials to deliver a project, known differently as the 4M of a construction project (NEALE and NEALE, 1989). As the authors underline, the allocation of the resources is costly. Therefore, it requires the right experience in the decision-making process to assess the right amount of the required resources for a specific project. However, the authors present this process as resource optimization. There are two common tools, resource-smoothing, and resource-leveling that PM uses for the resource optimization process. The application of the tools depends on the constraints and condition of each project, the phase when it is required to apply, or other external physical constraints;

- Resource smoothing is usually used when time is constrained and hand over the project on time is required.
- On the other hand, resource leveling is used when resource availability is constrained and can not be increased. PM estimates the completion date based on the available resources.

It is notable to mention that using free float adequately in resource smoothing needs to be considered (NEALE and NEALE, 1989). A summary of the comparison between the two tools is presented in the table below.

	Resource leveling	Resource smoothing
1	Resource limited scheduling technique; Importance is given to the limited resources	Time limited scheduling technique; Importance is given to the duration of the project
2	Removes all resource conflicts	Removes as much resource conflicts as possible; but, may not remove all resource conflicts
3	May not require additional resources	May require additional resources to address left over resource conflicts
4	Activities may be shifted beyond the float available while rescheduling the activities	Activities are shifted only to the extent of the float available
5	Generally, the project duration gets extended	The project duration remains the same
6	May change the critical path	No change in critical path

Table 1: Resource Leveling and Smoothing. (Arumugam, 2018)

2.7 Monitoring and Controlling

The project baseline is the proposed plan and a tool to monitor the project process against it. The so-called corrective actions need to be taken to control the process to ensure that the project progresses as planned and avoids deviations that might occur (Kidston and Haward, 2015). In order to monitor and control the project, data need to be captured from the site and compared with the planned process and make the necessary decision whenever it is needed. The tools and techniques below are available to assist PM to control and monitor (NEALE and NEALE, 1989);

- Cost/value comparison
- Key resources
- Key activities
- Cash flow
- Earned value

2.8 Barriers to Traditional Planning

Traditional planning has been practiced by PM for a long time, although this approach presents many weaknesses. One of the drawbacks of the traditional approach is the participants' level of involvement (Ballard and Tommelein, 1999; Koskela et al., 2002;

Tommelein, 2017). This approach consists of a schedule, which is prepared by the PM, and all the contractors and subcontractors should align with it. Therefore, the contractors are motivated to fulfill their respective activities' contractual requirements and not collaborate with other trades. As Koskela (2002) mentions, such a thing might compromise the scope of the project. The lack of adequate information for the consecutive activities is the reason why, in many cases, the participants struggle to follow the plan. A summarized list of the barriers to using traditional planning in construction projects is presented as follows:

- Lack of indicating the location where the activities happen. Hence, tracking the project progress is challenging as the percentage of completion is difficult to quantify. On the other hand, the overlapping of the working trades in the same location is difficult to be avoided, causing waiting times and cost increasements.
- The schedule deviation, productivity rate, and waste production are complicated to detect, especially in a large-sized project; therefore, assessing the risks associated with the project is not made at the right time.
- The traditional construction approach does not effectively support resource usage efficiency and lacks in identifying repetitive processes to create a steady workflow.
- In traditional planning, pushing for more speed is the principal methodology of implementation. In many cases, this method does not consider the other aspects of the construction's triangle of constraints; while aiming to increase the implementation time, the quality and cost are not in the focus of the contractors. A comparison of the push and pull method is made in the other chapters of this thesis.

3. Lean Management

This chapter will introduce Lean Management, the principles of the Toyota Production System, and how it was adapted to use in construction projects. In addition, the foundations of the theory of production in construction projects will be discussed.

3.1 Introduction

The term “Lean” was first introduced by Toyota Car Production Company to improve its production system based on client demand (Alarcòn, 1997; Howell, 1999). The Lean philosophy was initially introduced as a production control method and was based on different simple approaches related to production concepts and operations regarding quality control. This philosophy was developed by Taiichi Ōno (Ohno), which introduced the Just-in-Time (JIT) system and Total Quality Management (TQM) (Ōno and Bodek, 1988). Engineer Ohno followed the work of Henry Ford in the successful implementation of a continuous manufacturing system at Ford automobile (Lander and Liker, 2007).

3.2 Toyota Production System

The Toyota Production System (TPS) was mainly based on three core principles: (1) Waste Reduction; (2) Continuous Improvement; (3) Teamwork (Liker, 2004). According to the author, the system consisted of the same principles that Ford Automobile had already developed from 1930-1950. The difference was that, while Ford did not have limits for production, Engineer Ohno, who was the responsible engineer to increase the production capacities of Toyota, considered eliminating all types of waste, and the production would rely on the real customer order. Therefore, no inventories or intermediate stores were considered (Alarcòn, 1997).

The TPS concept does not involve a certain production time (Howell, 1999). According to Howell, the time for producing a certain type of car was defined by the need for production. In this sense, the production line would adapt to the time that the demand would impose. In contrast with the American system, where pressuring for production can cause a lot of faults, increase waste and eventually affect the production price, Engineer Ohno focused more on building a very reliable workflow by eliminating the waste, producing a qualitative product, and controlling the price (Liker, 2004). This vision would require tight coordination between all the participants and further adaptive measures (Lander and Liker, 2007).

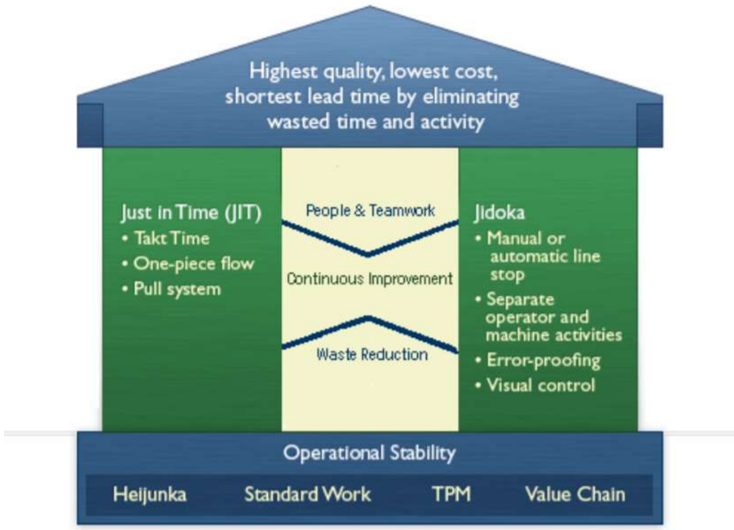


Figure 4: House of Toyota, TPS. (Construction Industry Institute, 2007)

Following Ohno's concept, all the perspectives of the production would adjust to afford and smoothen the process (Howell, 1999). Considering that clients have different requirements and that during the production process, many defects occur, the aspects of perfecting this production methodology widen and complicate the expected workflow. The production line was a straightforward process that each production segment is done by the same resources and in the same order. Hence, optimizing the production flow and increasing the efficiency of each production and assembling sequence were the foundation of this methodology.

A remarkable decision that Engineer Ohno took was to stop the production line when a defect occurred to avoid rework (Liker, 2004). On the other hand, halting the production would affect all the other successive and preceding sequences, not complying in this way with the "No-waste perfection" concept. Liker states that avoid reworking make sense in such a methodology but would require chirurgical precision and efficiency in all the production activities. In this sense, optimizing each individual production segment's performance was vital in reaching the expectancies and meeting the customer demand.

In order to optimize the performance of the production line, the production system was converted totally visible. All the participants would have the information on how the production pace is proceeding, and the results would illustrate a high sense of collaboration in terms of individual decisions in supporting the workflow. The need to have a broad managerial group also decreased (Ōno and Bodek, 1988).

To further improve this methodology, the production workflow of the new models would highly depend on the respective designs (Shingō, 1998). An extensive analysis of the latest models was necessary to highlight the compliance with the production's line flexibility boundaries. While the engineering solutions were contracted to suppliers, different commercial contracts were developed in order to decrease the price and allow the suppliers to enter the Lean production methodology of Toyota (Lander and Liker, 2007; Liker, 2004).

3.3 Theory of production in construction

The theory of production in construction derives from TPS developed by Engineer Ohno (1988). Based on this theory, the time to produce a product will depend on the actual customer demand, and the production line and time sequences will be adapted based on the production load. However, when it comes to construction, many questions arise on quantifying the actual demand and setting the proper time cycles, which will include the physical state of the construction materials (Koskela, 1992). Nevertheless, different investigations are done related to production theory. Lauri Koskela explored the possibility of integrating this theory in construction and examined the performance of such integration.

In his dissertation 'An exploration towards a production theory and its application to construction' (2000), Koskela suggested the concept of "Transformation – Flow – Value (TFV)" on construction production through three simple management actions on the Production System (PS): (1) design; (2) Control; (3) Improve. The TFV concept is a paradigm of the car production that Ohno developed, and it is intended to present the steps that one activity goes through.

The transformation concept is the division of a production process into component processes. This means that in construction, similarly with all the other production systems, the “Product” has to be decomposed into smaller components. The physical and conceptual order of arranging these sub-processes, combined with other inputs such as material and resources, is called the production process (Bertelsen and Koskela, 2002; Koskela, 2000). The figure below conceptualizes the Transformation process.

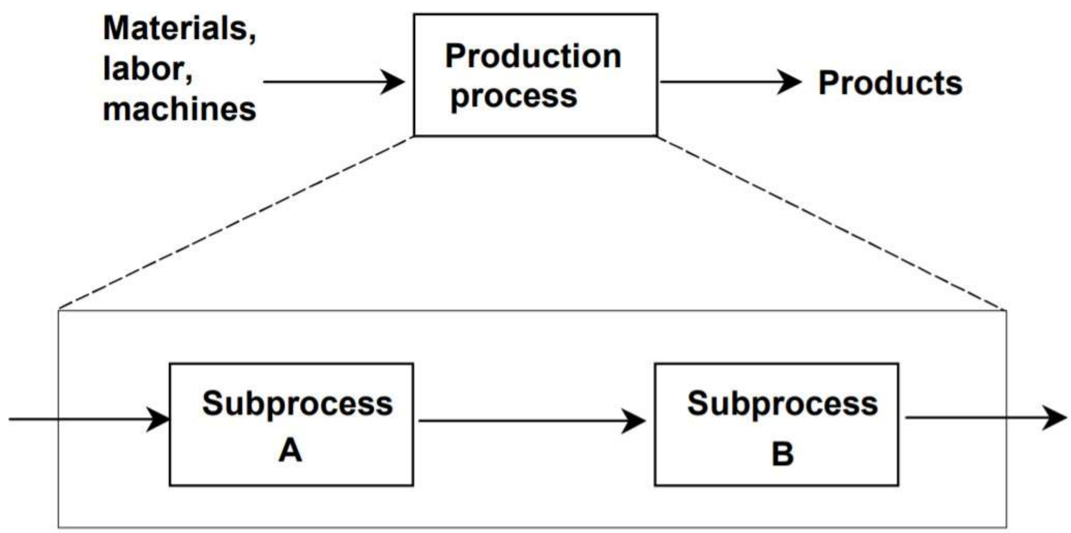


Figure 5: Koskela’s transformation process. (Koskela, 2000)

Traditionally this is known as the work breakdown structure (Tsao, 2005). In this context, one construction activity can be broken down into sub-activities. Considering this activity as a product to be delivered, also different aspects should be taken into consideration. The completion time of each sub-activity can be better controlled. This means that the control over the buffers boosts and the overall quality because defects can be easily detected and taken care of. Eventually, the cost of production decreases as it is easier to control the costs of each sub-process (Bertelsen and Koskela, 2002).

The “Flow” concept of production, according to Koskela (2000), differs drastically from the transformation. While in transformation, only the production process is taken into consideration, in the flow concept, time for each transformation operation is introduced to harmonize the production workflow, also named the Operation time. In contrast, the Japanese engineers of Toyota considered ‘flow’ as the process of passing the production sequences from one labor to another. In construction, ‘flow’ refers to the production and the operations in between activity (Koskela, 1992).

Koskela (2000) concludes that the general idea of creating flow is to synchronize all the processes and sub-processes, or activities and sub-activities, in order to create a reliable and balanced production system. This reliability, similarly to the TPS, depends on all the waste elimination. The combination of Operation and Transformation enables controlling the production system in terms of prioritization of processes. Therefore, the control over all kinds of wastes (as in TPS) is improved, variability can be reduced, and the process can be simplified in order to make it more flexible and transparent.

The goal of creating a balanced workflow is to develop a continuous process and maximize production efficiency (Bertelsen and Koskela, 2002). According to the authors, improvements are always necessary, and the unforeseeable conditions should also be taken into consideration. Hence, the operation time for each sub-process is equal, and the used resources define the pace. In this sense, when a sub-activity is analyzed to be faster than the previous one, the crew will be adapted to have the same pace as the previous one. Generally, the operation time is conditioned by the pace of the sub-process that requires more completion time.

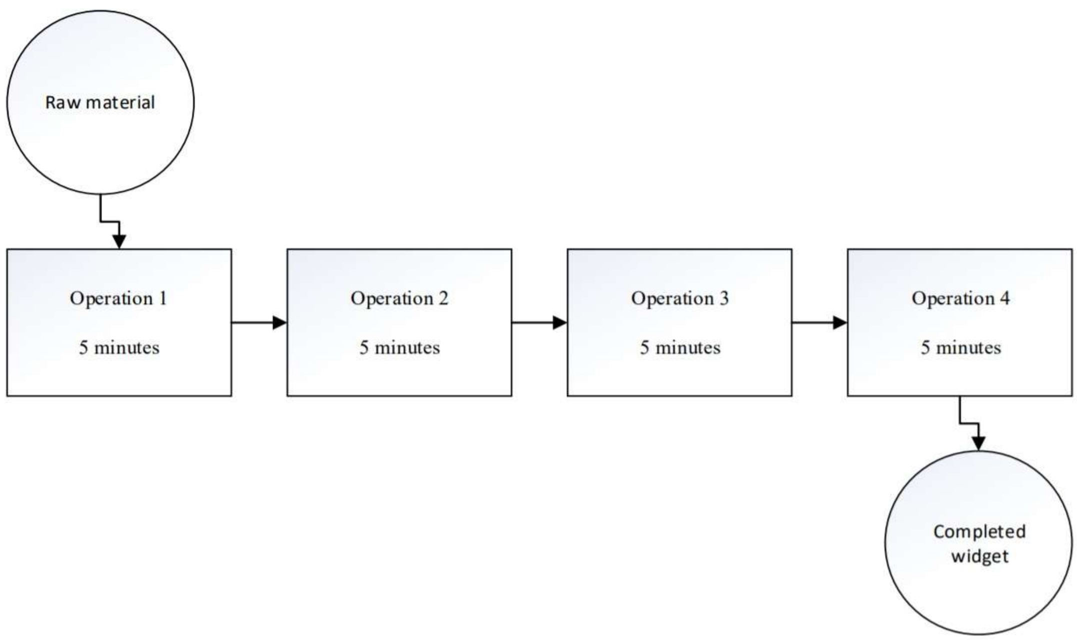


Figure 6: Simplified scheme of creating the flow. (Frandson, 2019)

In the “Value” concept of Koskela’s TFV, the focus is on the customers, in analogy with TPS customer demand. The idea behind is to create a relationship between the ‘supplier’ and the ‘client’ (Frandson, 2019). According to Koskela, the client’s satisfaction should be the foundation of conceptualizing the production process, and transformation and flow concepts are integrated for the client's sake. Nevertheless, the physical state of the production takes a significant role, as well as the internal objectives of the 'supplier' (Koskela, 2000).

Focusing on the customer requirements, as those requirements define his satisfaction, means that all the processes that do not generate an added value are considered waste and will be eliminated by the production system (Koskela, 1992). This theory also considers the supply chain as an integral part of production. Suppliers should provide the required deliverables in the time needed, with the required quantity, and on the required quality.

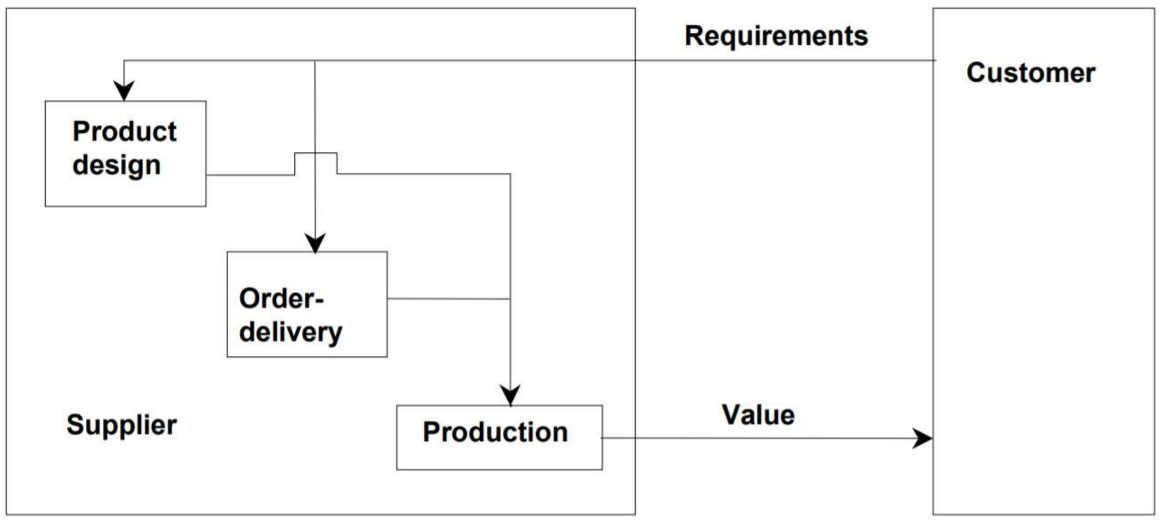


Figure 7: Koskela's Value generating scheme. (Koskela, 2000)

This tight coordination requires collaboration on a broad specter in order to build an adequate framework for the production process (Koskela, 1992). Failing to meet all the aspects of any process compromises the whole production, and it might be fatal in terms of project development. Koskela (2000) advises that a transparent process is required. All the participants should be able to understand the requirements of the client and the requirements of the designed production system. Simultaneously, a commitment to meet all the process expectancies by all the production sub-processes is vital. For this reason, the assessment of the process and the overall value generated to the client should be enabled (Koskela, 2000).

3.4 Construction Lean Management

The first views of Lean in construction, as mentioned above, are presented by Lauri Koskela (1992) in its report: “The Application of the New Production Philosophy to Construction”. The term Lean Construction was introduced one year later by (Koskela et al.) when they presented the report on the foundations of Lean Construction. In addition to Koskela and Ballard, a vast contribution to Lean Construction is given by Glenn Gregory Howell, who is the co-founder of the Lean Construction Institute in 1997.

However, the construction industry remains traditional and faces obstacles in perceiving new methodologies and technologies (Aziz and Hafez, 2013). Delivering a construction project differs from other project production systems because of the unique complexity of design that the construction projects have, the size of the projects, and the number of stakeholders involved in this process (Ballard and Howell, 2003). According to the authors, while the other production systems have their respective workstations, in the construction projects, the workstations should be built at the location of the project and move to implement different components of the project. For this reason, implementing without other considerations the Lean principles into construction sites are very challenging.

Nevertheless, the implementation of Lean management does not involve utterly new construction management techniques (Ballard and Howell, 2003; Best et al., 2002; Koskela et al., 2002). Instead, it strengthens the existing management principles by focusing more on eliminating wastes and non-value adding activities, increase collaboration between all the participants and flatten the hierarchies by increasing the transparency of all the process, cost optimizations by building continuous workflow, and implementation of the supply chain in the process as an integral part of it. The Lean production of Toyota focused on eliminating all types of wastes, developed by Engineer Ohno, has been used as a pattern paradigm in Lean construction (Ballard and Howell, 2003).

Construction management techniques combined with nowadays technology define the success of a project (Ballard and Howell, 2003). According to the authors, the Lean implementation in construction management requires a commitment to all management levels and a comprehensive participatory level. The benefits of Lean principles, just like traditional approaches, involve meeting the triple constraints of the construction management: finishing the project on time, on budget, and the required quality.

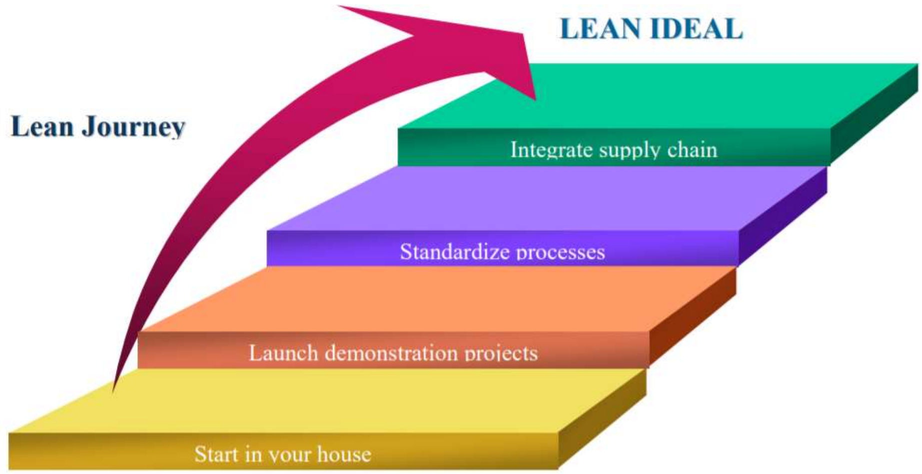


Figure 8: Lean Journey. (Construction Industry Institute, 2007)

However, Aziz and Hafez (2013) state that lean management differs from the traditional approach to managing construction projects. Although the objectives remain the same, lean management is always under continuous adjustments during the construction process as it tends to reach continuous improvements based on the conditions or circumstances that one activity or the project, in general, might be.

Lean implementation, according to Picchi and Granja (n.d.), lays on five main principles: (1) Value: Identifying the customer’s needs, highlight all the activities and aspects that add value to the project and affect the expectations of the customer; (2) Value Stream: Disregarding all the elements that do not add value to the project, avoiding rework, avoid wastes, allocating the resources in the right place, in the right time, and the right quantity, eliminating the waiting time; (3) Flow: create a continuous and reliable workflow by consolidating all the supply chain; (4) Pull: Produce what is needed, avoid unnecessary pressure to ensure the quality of the project; (5) Perfection: improve the process continues in order to deliver a project that meets all the expectancies.

However, the above principles remain in broad terms as the complexity of the construction enforces for more detailed principles in case Lean is the purpose. According to Aziz and Hafez (2013) and Construction Industry Institute (2007), the implementation of Lean in construction goes into four significant categories, known differently as

4P, and a total of fourteen principles distributed into these categories. These principles are also known as the principles of TPS.

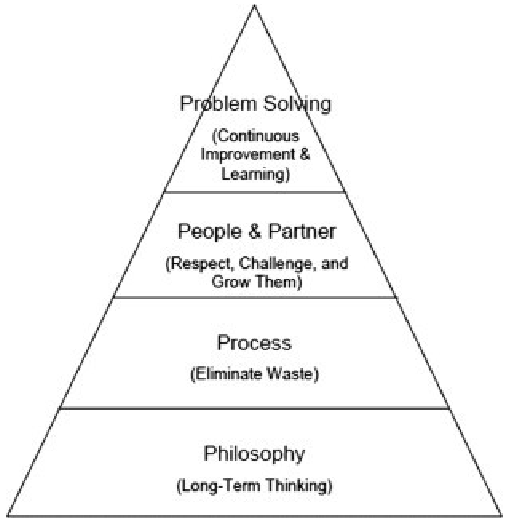


Figure 9:The 4P in Lean Construction. (Construction Industry Institute, 2007)

3.5 Work Structuring Method

The work structuring was known differently as the production system. Ballard (1999) explained the first concepts of the work structuring method in Lean construction. According to the author, the work structure is the design of the construction operations, processes, sub-processes, and alignment with the supply chain and resources. The work structure focuses on breaking down the product into manageable pieces (work chunks) (Ballard, 1999; Tsao, 2005).

Ballard (1999) explained that the objective is to create a continuous flow and considers different work activities as cyclic processes that need to be optimized. According to the author, the work is broken down while addressing the following questions:

1. What are the possible chunks that work can be assigned to production units? (The question to be answered before going to production.)
2. What is the sequence of the chunks?
3. How will the work be delivered from one production unit to the other?
4. Will the production be a continuous process, or will there be the need for decoupling buffers?
5. Which work needs to be decoupled, and what is the duration of the buffer?
6. When will various chunks be executed?

Tsao (2005), in her dissertation, simplified the language of work structuring method in three main terms (terms also used by Ballard): (1) work chunks; (2) Production Unit; (3) Handoff. Therefore, the production process is presented as the work to be done, executed by the specific trade, and completed (handoff) for the successor production unit can perform its correspondent work chunk.

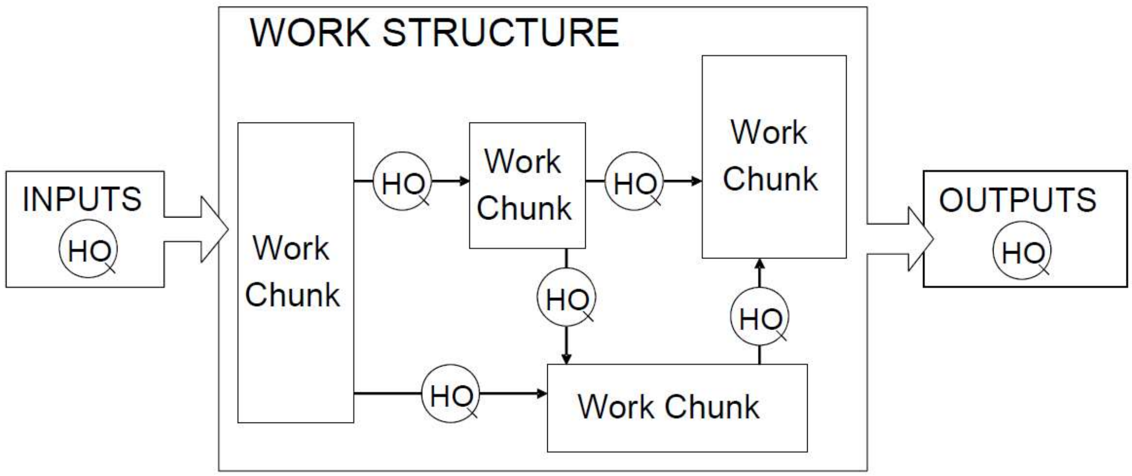


Figure 10: Relation between the work chunks. HO = Handoff. (Frandson and Tommelein, 2014)

Takt Time Planning is used as a work structuring method to increase the construction sites' efficiency implementing a rational and disciplined workflow (Frandson, 2019). Ballard and Tommelein (1999) and Frandson and Tommelein (2014) categorize TTP as a process that happens between the master schedule and lookahead processes.

The objectives of using TTP as a work structuring method are presented by Tommelein (2017). According to the author, TTP is a feasible phase schedule which aims to:

1. Include the working trades into the decision making, by deciding to work in the way which suits them better.
2. Balanced crew sizes, which ensure a continuous process.
3. Avoid crew overlapping in an area.
4. Deliver work chunks on the same duration basis.
5. Balance the plan while increasing the pace of individual work chunks.

4. Productivity improvement through Location-based Scheduling

Takt Time Planning considers the duration and location of the activities. Location-based scheduling techniques have shown major productivity improvement in many projects. In this section, an introduction of Line of Balance (LOB), Location-Based Management System (LBMS), and Point-to-Point technique will be discussed in the further sub-chapters.

4.1 Introduction

Construction engineers focus on shortening the project implementation time, relying on the CPM features (Rezaei, 2015). The traditional approaches, however, do not focus on improving productivity and using the resources efficiently to shorten the duration of the project. Sacks and Partouche (2010) present the significant productivity improvements in the Empire State Building the LOB scheduling technique. The implementation frameworks of the location-based scheduling techniques provide the theoretical approach of construction productivity improvements, which will be used for this research's objectives.

4.2 Line of Balance

The LOB, although it is a linear schedule method, involves a set of repetitive activities and processes, which can be developed horizontally (infrastructure projects such as roads, bridges, etc.) or vertically (high-rising developments) (Arditi et al., 2001). This technique, introduced in construction while building the Empire State Building in New York, enables balancing the pace of activities so that the production rate is uniform and without gaps (Sacks and Partouche, 2010). Specifically, the development of one activity is steady, and it is illustrated in a graph as a line conveyed as completion of work quantities over time (Arditi et al., 2001).

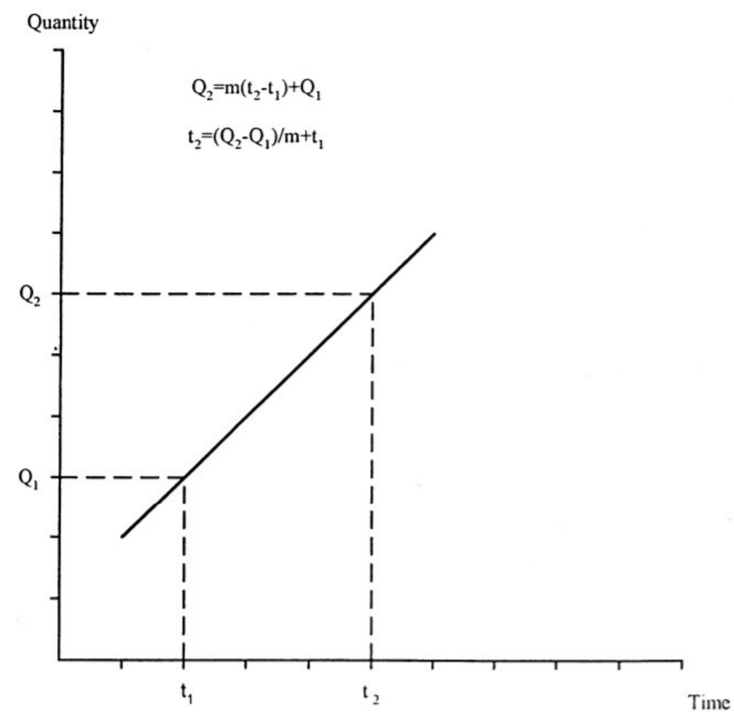


Figure 11: Graphic illustration of the LOB. (Arditi et al., 2001)

In figure 11, the Y-axis expresses the amount of work that needs to be completed, and on the X-axis is illustrated the required time for the completion of the work. The slope of the activity is the overall rate of productivity for the activity. An activity with a higher slope indicates that this activity will be completed faster (Arditi and Albulak, 1986). During the monitoring and controlling phase, the degree of readiness consists of assessing the slope of the activity at a specific time. In Arditi and Albulak's case study related to the construction of pavements (1986), the pace of the activities depends on two main factors: (1) the production rate of the workforce; (2) the quantity of the work to be completed. Therefore, the simplified mathematical calculations adopted by Arditi and Albulak (1986) are described in the equation below:

$$\boldsymbol{D = Q/m}$$

Equation 3: Calculating the duration of one activity equation. (Arditi and Albulak, 1986)

m = production rate (unit/t)

t_n = time

Q = quantity (unit)

D = duration of activity (time)

This equation can be adapted and used for different purposes during the preplanning phase or the implementation phase. During the preplanning stage, the production rate would be defined from various surveys on similar works and will come as an average of the amount of work than one crew produces on a time basis (hours, days, weeks). This will define the number of crews needed to reach the desired time milestone. Nevertheless, an analysis of the space how these crews are going to be distributed will also be required (Frandson, 2019).

On the other hand, in construction, there are many unforeseeable events that may affect the schedule (Sacks and Partouche, 2010). During the monitoring and controlling phase, equation one can be adapted to assess the degree of readiness, decide whether there is a need for more workforce, or analyze the pace of a particular activity for a specific time interval. Hence, the degree of readiness will be $Q_n = m * t_n$, where n is the particular time term that the analysis is done. The production rate of the crews, as discussed above, it has a percentage of assumptions, so during the execution, the real production rate can be detected in order to have accurate information on deciding how to further proceed according to the schedule (Arditi and Albulak, 1986).

Equation one can be expressed as illustrated in figure 11 in the case of the assessment in a certain period of time is necessary:

$$Q_2 = m * (t_2 - t_1)$$

Equation 4: Assessing the quantities in a period equation. (Arditi and Albulak, 1986)

The master schedule can be optimized to be more efficient and reduce the unnecessary flexibility measures of a plan. Once the work breakdown structure is done, the relationship between the processes is analyzed. The duration of the activities is done using equation 1. The first optimization of the plan can be used by eliminating the waiting times of the activities, which is also the foundation of the LOB. Based on the information that can be extracted from each activity, the schedule can be further improved by increasing or decreasing the pace of the activities by adding or removing crews (Arditi and Albulak, 1986).

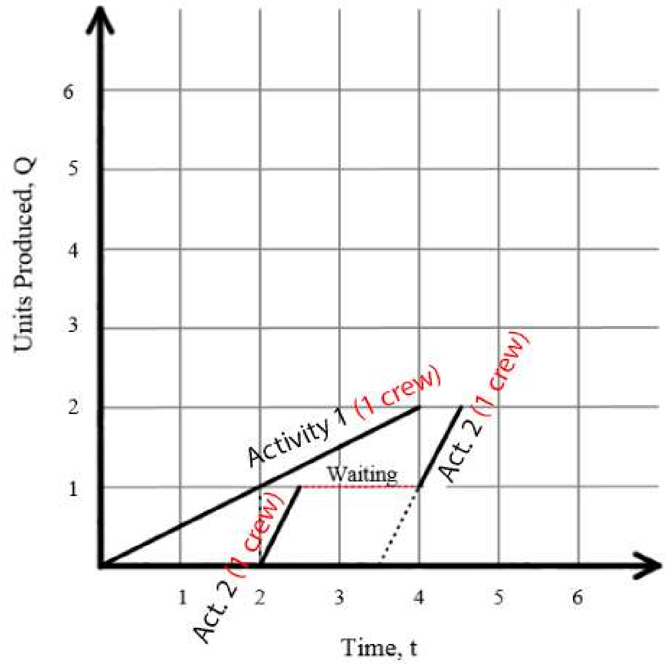


Figure 12: Illustration of waiting times between activities because of different production rates. (Frandson, 2019)

Schedules accepting a waiting time are risky, especially for the returning to work periods. When it comes to subcontractors, they will use the waiting time to focus on other projects, potentially complicating the bearing on the due date (Arditi and Albulak, 1986). On the other hand, time in construction means cost, and unnecessary delays will result in significant cost overruns, and the construction project exposes to the failure risk (Hjelmbrekke et al., 2015; Kaliba et al., 2009). In this context, the LOB scheduling technique helps in minimizing those risks and enabling schedulers to have the potential to synchronize the schedule (Arditi et al., 2001).

The synchronization of all the activities (figure 12) is done by manipulating working crews based on each crew production rate (Arditi et al., 2001). Mendes and Heineck (1998) presented a case study, using the line of balance technique for multi-story buildings, describes how the crews' calculations are done to synchronize all the main activities in order to have a steady production pace. This case study illustrates how the activities that have a high degree of dependency are grouped in order to enable planning linkages for all the activities. The pace of each activity this way would depend on the nature of the grouped works. This group of works during the execution phase was exploded so it could be better managed and reach the schedule milestones (Mendes, JR. and Heineck, 1998).

Kankainen and Seppänen (2003), while in the early stages of building a software related to LOB (DYNAProject ™ as a predecessor of Viko Schedule Planner, which will is discussed on the following chapters), which would optimize the control aspect of the project (where other related software were lacking), summarized the findings of the theoretical research over LOB into three main points *(italic text same as the source)*:

- *"The feasibility of the master schedule must be checked before production begins."*
- *"When actual production deviates from plans, control actions must be taken to put the project back on a schedule rather than updating the schedule."*
- *"Production control must ensure continuous workflow by use of free spaces."*

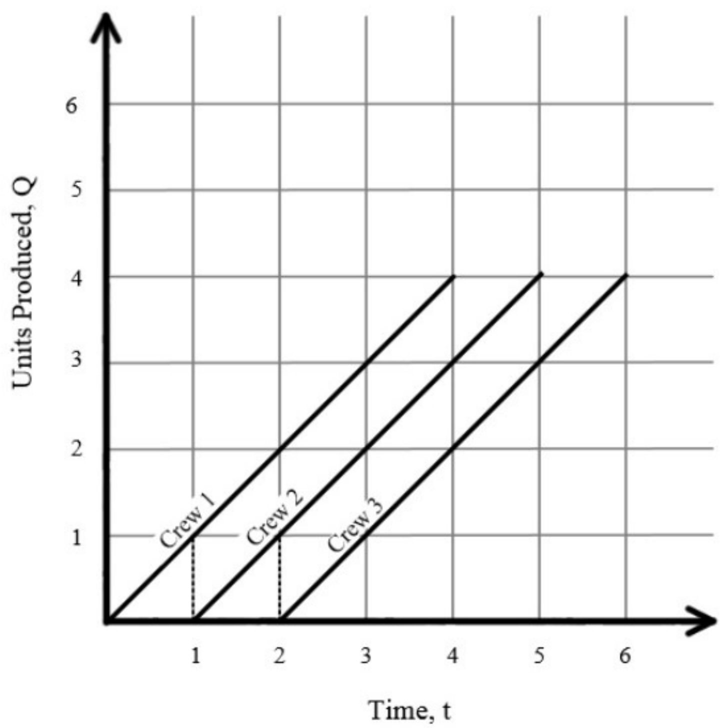


Figure 13: Synchronized LOB. (Frandson, 2019)

Nevertheless, this technique is not as popular as the other traditional scheduling techniques (Arditi et al., 2001). The line-of-balance, though it is a more powerful scheduling technique than Gant Chart, in terms of scheduling reliability, it is usually not recognizable by the site engineers due to different visualizations (Al Sarraj, 1990). It is not widely used because, in highly complex projects, which have numerous activities, it is difficult for the project participants to follow up when all the activities are scheduled on one master plan.

4.3 Location-Based Management System

The Location-based management system (LBMS) roots lie in the combination of two methodologies used in construction, the line-of balance, and the Flowline scheduling method (Seppänen et al., 2010). The approach of the LBMS is to build hierarchy levels, which will augment the discipline of the schedule in terms of the pre-planning and monitoring and controlling phases, improve efficiency and minimize the risk of the project failures (Kenley and Seppänen, 2009).

4.3.1 Planning phase

Due to the unique nature of the construction projects, considering the building as repetitive and continuous work to increase productivity and efficiency is not common (Seppänen and Kenley, 2009). Olivieri et al. (2018), in their recent research regarding LBMS, agree that the (CPM), which is widely used in construction, fails to improve the efficiency of the construction process in terms of clash avoidance (different crews might work in the same location, or waiting time is not controllable). The authors also describe how other aspects of a project that directly impact the reliability of the scheduling, such as the allocation and the right amount of resources, are highly improved while LBMS is used as a scheduling technique. LBMS, as the name suggests, is the technique that schedules the construction activities based on their location (Seppänen and Kenley, 2009).

According to Seppänen (2009), the location does not indicate the same quantities, the same group of activities, or the same completion time for the area. Rather it depends on the nature of the activities, a particular component location, a specific building technique, or logical and physical constraints of a certain element or process. The author states that this method is not entirely different from CPM. The interdependency relation of the CPM method is used to link the activities and express the logic of construction. In addition, the linkage is used for the internal processes of a certain activity and for the activities that have a different location but have a linkage constraint with one another (Seppänen and Kenley, 2009).

Seppänen (2009) summarized the features of the LBMS and the new concepts. Hence, the Work Breakdown Structure in LBMS is done through locations. This is the first step in scheduling the LBMS method. This structure also contains the quantities, which are spread accordingly, and also the sub-processes of the activities on this location. The duration of these activities depends on the work quantities and the production rates of the planned resources. The author considers the activities as a continuous process and agrees that this way, the efficiency of the working trades will be improved. In order to enhance the workflow for steady production, the concepts of CPM are used to link the same activity, which happens in different locations to create a continuous process, but also connect different activities with one another. This is called, according to the author, “the layered CPM”. Buffers are used between the activities to plan in advance any unforeseeable event or different constraints, mitigating this way the risk of delays. The author states that there can be added two kinds of buffers: (1) space buffer; (2) time buffer. The first one is a location-based buffer, and it means that a particular activity can start or finish when the correspondent linked activity is happening in a certain location. The second one is related to time. Any activity can also be spliced, if the nature of the activity is like this, or for the reason that this improves the master schedule (Seppänen, 2009).

4.3.2 A case study using LBMS in the planning phase

The LBMS method was for a project located in Helsinki, Finland. The purpose of this case study is to understand and illustrate the principles and benefits of the application of LBMS in a construction schedule. For conducting this case study, the information on production rates was necessary. As the accuracy of the plan is not on the focus for this training case study, the production rates are not given according to official databases of public statistical institutions. Therefore, the used production rates are based on the information discussed during the “International Site Management” class with Mr. Mikka Lindholm. Vico Schedule Planner is used to generate this schedule.

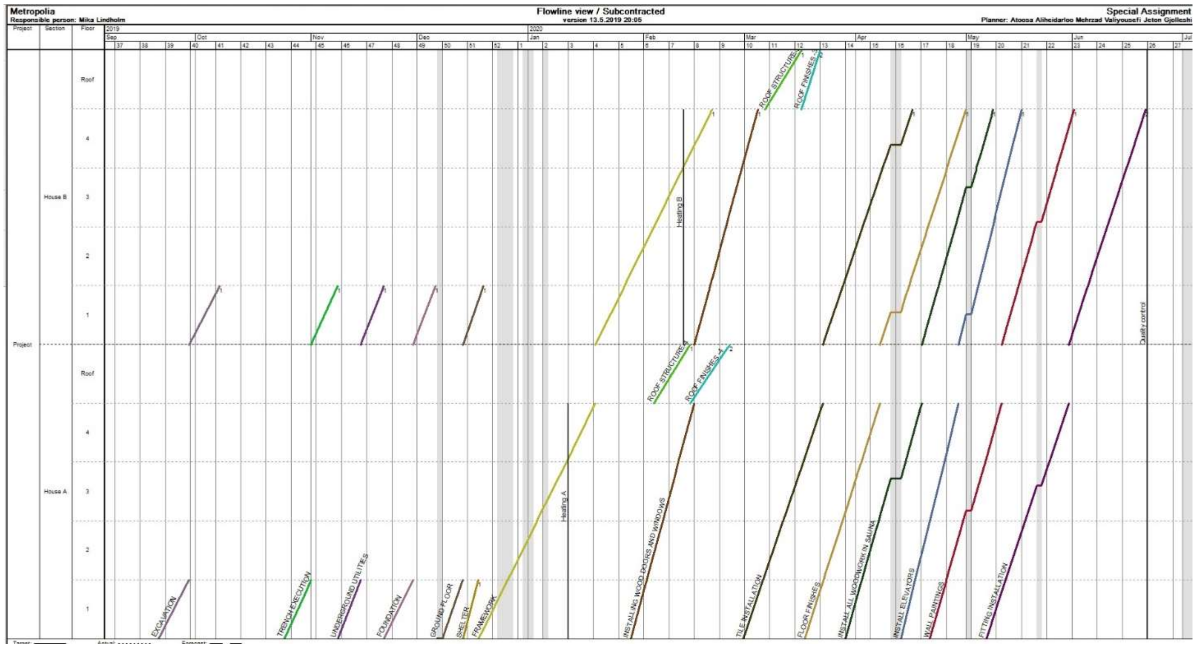


Figure 14: Construction Schedule using LBMS planned by the author via Vico Schedule Planner

In figure 14 is illustrated a schedule of the case study construction project located in Finland, consisting of two sections by five floors each using the LBMS method. The activities are presented with different colors to avoid confusion on the executing participants. The schedule is done following the steps described in the book of Kenley and Seppänen (2009), over the usage of LBMS in construction. Therefore, after the Work Breakdown Structure and quantities accordingly, a grouping of the activities is done based on the nature of the works. The quantities of each group of works are distributed through different locations (i.e., when working groups are related to roofing, the quantity of works is 100 % in this specific location).

The duration of each activity, in this case, depends on the working crews. Nevertheless, the production rates can also be a result of the working labors planned by the scheduler to complete a certain quantity of activity. This case is prevalent on Backward Scheduling when the due date is already known (Seppänen, 2009). Vico Schedule Planner is powerful software, which enables these kinds of calculations automatically. However, the equation behind the estimates for the activity's length, according to Seppänen (2009), is as follows:

$$D_A = Q_A/(P_R * Nr.labour)$$

Equation 5: Simplified equation for the duration of the activity in the LBMS method.

Where:

D_A = duration of the activity
Q_A = Quantity of the activity
P_R = Productivity rate

The next step for completing the schedule was adding the interdependencies between the activities and buffers subject to the nature of dependent activities. The optimization of the plan has gone through different stages. The first optimization consisted of the schedule itself, avoiding the clashes between various activities, increasing or decreasing the number of laborers. The other optimization consists of resource distribution, which will also affect the general plan. The focus of this project was to see the optimization potentials of the LBMS. Therefore, the cost optimization of the project and supply chain schedule were not considered and will be further discussed in the other chapters of the thesis.

4.3.3 Monitoring and Controlling

Seppänen (2009) describes that the LBMS improves the quality of the implementation process, as the combination of the activity with its location enhances the possibility to generate more data valuable for decision making. Using the LBMS for monitoring and controlling phase can enhance the advancement assessment of the planned activities, generate data to track the performance of the working crews, and forecast the potential progress of the project based on the actual productivity of activity's development (Frandson et al., 2015).

The forecasting feature of the LBMS introduces the approach of taking early corrective actions to keep the project "on track" (Seppänen et al., 2014). According to Seppänen's research (2009) over the LBMS production control, in contrast with the CPM where the actual time terms of the activities are updated to have an overview of the potential delays, the LBMS introduces daily production updates to assess the progress trend and enable early corrective decisions. The author highlights the importance of the location, and it relates to the significance of each activity's location with the overall progress of the project. Thus, the chain effect of the delays is avoided, and the project is delivered diligently, not compromising any aspect of the approved plan (figure 15) (Seppänen, 2009).

However, these features do not exclude CPM approaches (Seppänen and Kenley, 2009). Therefore, the LBMS can be used the same way as CPM, with a higher level of accuracy. The main difference in the dependency relationship is the existence of the buffers to minimize the risk during the implementation phase and integrate a certain level of flexibility to the schedule (Olivieri et al., 2018). According to these authors, the CPM logic can be even generated in the LBMS when this logic is applied between the grouped activities. The leveled detailing of the dependencies in this group enables an accurate controlling and details who own the float in location level. Moreover, integration of the forecasting feature on LBMS does not affect the approved schedule, but it signals a warning, which indicates that the project may be subject to delays (Seppänen, 2009).

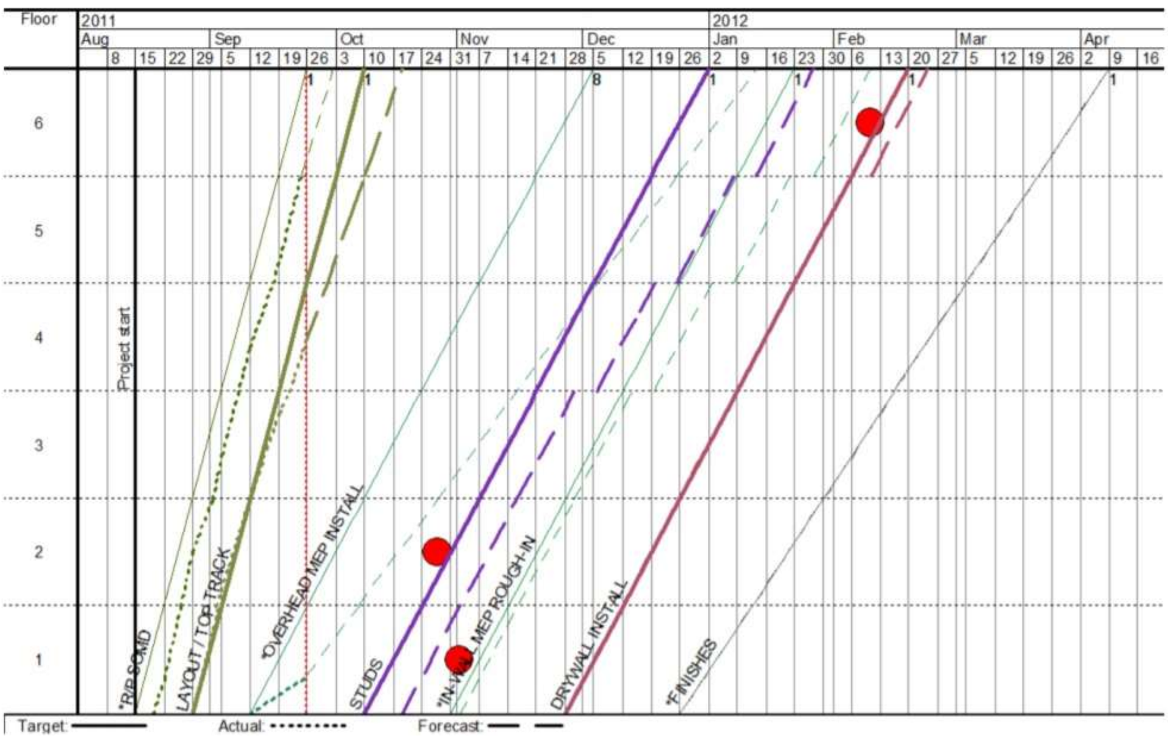


Figure 15: LBMS schedule forecasting, using Vico Schedule Planner. The red dots indicate the activities that are expected to get affected if the predecessor is expected to have the same production rate, and the dashed activities represent the deviation of the plan if the "Overhead MEP install" activity is running late. (Seppänen, 2009)

Nevertheless, there is no detailed research that relates to the corrective actions of the LBMS with the financial aspect of the project. Moreover, different case studies illustrate that major improvements are made in terms of project delivery time (especially in interior works, as they offer more possibility for the combination of the location and activity repetitiveness (Seppänen, 2009)). Still, there is no detailed research on how the working crews' continuous increase is allocated in different locations. Though the overall progress, as Seppänen states, is increased, the efficiency of the additional working units and the alignment with the location is not clear as their nature mainly characterizes the location of the activities.

4.4 Point-to-point technique

The point-to-point (PTP) technique in construction planning consists of fragmentation of one activity to avoid overlapping with the other activity (Hajdu, 2015). Hajdu used this technique to connect to interdependent activities by inner points, representing particular progress, a certain amount, of a specific time. This means that when the predecessor activity achieves one of the target points, the successor activity starts to progress. In this consideration, the successor activity will have a controllable pace, so there will be no clashes between them. The author used the PTP technique for linear repetitive activities (horizontal or vertical). The fragmentation of the activities creates certain dependencies indicated in a particular location, as illustrated in figure 16.

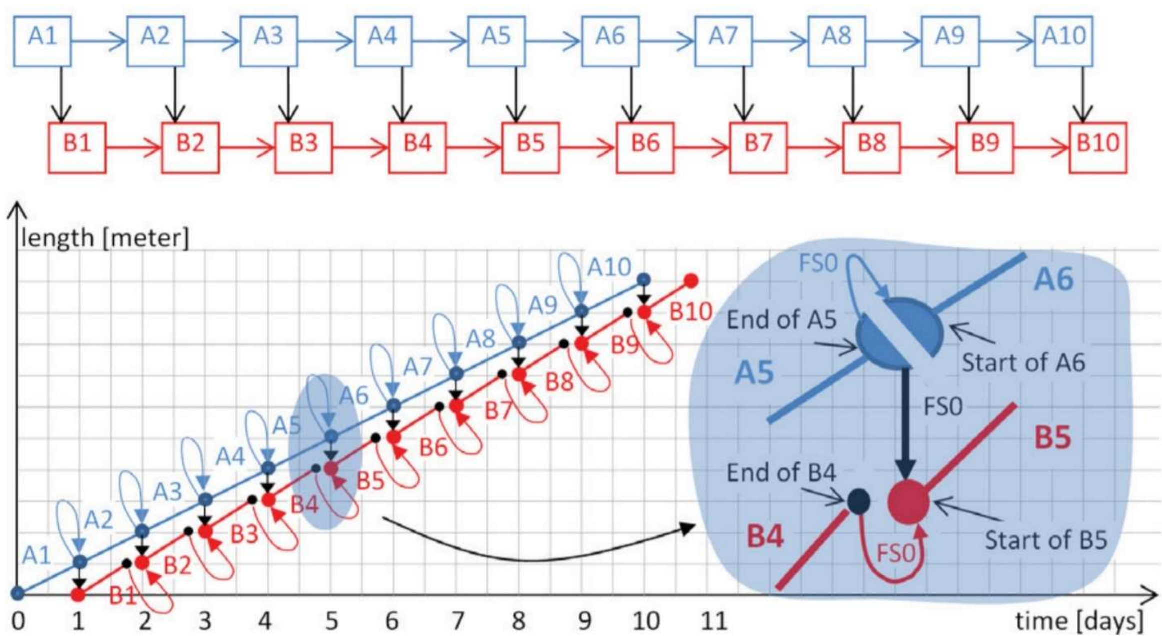


Figure 16: Point-to-point methodology, F->S dependency. (Hajdu, 2015)

As Hajdu indicates, the blue activity is separated into smaller activities, which specifies the location of each segment. This segmentation will suggest when the red activity will start. In this case, the blue activity will start in another location and will happen in parallel in different segments with the red one. Brioso et al. (2017) compares professor' Hajdu research with other location-based scheduling and implies that there is no right theoretical background to provide a continuous productivity flow.

On the other hand, Hajdu agrees that this methodology provides limitations in terms of continuous workflow because of the waiting time that the successor activity in different segments might have. Likewise, he admits that when the schedule is complicated, tracking the progress and dealing with numerous fragments makes it challenging for the participants. However, Hajdu developed a mathematical algorithm to ensure continuous workflow, which, according to the author, is not friendly with a major of planning software (Hajdu, 2015).

5. Takt Time Planning

Takt is a German word, which indicates the "rhythm" (Frandson et al., 2013) or the regular frequency-time that an activity can be done or delivered (Haghsheno et al., 2016). As Haghsheno et al. (2016) refer to, there is a structured way of progression when there is a rhythm. The structure of the production defines the process, which is the regular way of sub-processes of activities. The completion time of one sub-process, under the condition of the same completion duration, as Frandson et al. (2013) refer, is named Takt time.

5.1 History of Takt Time Planning

The arranged production processes to increase productivity were used earlier than the industrial revolution, in the 16th century to produce ships in Venice (Haghsheno et al., 2016). According to these authors, in those times, the need to build ships from states was high, which led to new philosophies of production systems.

Haghsheno et al. (2016) state that the takted processes met a primary usage at the beginning of the 20th century, where they were highly applied in major industrial production systems. The authors recognize that Henry Ford was the pioneer of this methodology by adopting it to increase the production capacity of his automobile production lines. His philosophy that continuous production would lead to time improvements and the more economical product was validated with "T-Model Ford", whose price was lower than the competitors of that time and its assembling time considerably shorter (Haghsheno et al., 2016).

Takt was also embraced by the German industries, especially the aviation one, which set exact intervals for the processes of their production lines (Haghsheno et al., 2016). According to the authors, the production and the assembly line were synchronized, and they were both considered an integral part of the product production. The Lean Enterprise Institute explains in their article "Brief History of Lean" that due to the collaboration that this aviation industry had with Mitsubishi, Takt was first introduced to the Japan production systems, where Toyota engineers adopted it for their assembly line (Lean Enterprise Institute, 2015).

Norman Bodek, in his re-publication of “The Shingo System for Continuous Improvement” (1998), explains that Toyota used Takt for its “Just-in-time” principle of TPS (refer subchapter 3.2), which was a revision of the methodology used by Ford production line. The invention of TPS by the Toyota engineers consisted of arranging the production time for one product based on the demand rate for this product (Shingō, 1998). Shingo explains that the assembly line would adapt to reach the time target of producing one product, while the engineering solutions were outsourced. In order to offer a wide variety of assembling line for different automobiles models, the Takts between the processes were flexible in terms of design.

The most similar case of Takt in construction was described by Tommelein (1999) with the Parade of Trades' description. The TTP method in construction consists of arranging the same production rate for each activity by aligning the resources and location to create a steady workflow, increasing resource allocation efficiency, and creating a production environment with improvement capabilities (Frandson et al., 2013). According to these authors, this term has been used in construction to indicate the planning methodology, which deals with repetitive activities, by creating a sequence with the same duration that repeats in different locations. These specific locations are called Takt zones (Frandson et al., 2013; Heinonen and Seppänen, 2016)

5.2 Takt in industrial processes

Lean principles have been more embraced by the automotive industries (Haghsheno et al., 2016). However, the designed Takt for each manufacturing company depends on the product, and the demand defines the operating rates. The production and assembling lines are designed in a way that the combination of the manpower and the machines will have the same Takt time. Takt, in this sense, is the pull strategy of the production systems. This means that it is adjusted based on the demand to avoid overproduction. One example would be the Porsche automotive company, which, based on the market absorbance, arranged a Takt of five minutes (Motzko, 2013).

The most famous company which integrates Takt, as discussed in other chapters of this thesis, is certainly Toyota, which builds their famous TPS based mainly on two primary principles which consisted of quality and time; Specifically “Kanban” and “Just-in-Time" (Lander and Liker, 2007). The equation following their principle of production, adapted by Hanghsheno et al. (2016), is as follows:

$$Production\ takt = \frac{time\ available\ to\ deliver}{amount\ of\ demand}$$

Equation 6: The equation for Takt production. (Hanghsheno et al., 2016)

The Takt production, in this case, refers to one product. The production system, in this case, will be designed to integrate the assembly line, which, according to Shingo (1998), consists of processes and operations. The Takt of processes and operations mathematically would be expressed with the division of the "Takt Production" to the number of processes and operations (Shingō, 1998).

However, Shingo (1998) states that there should be a clear distinction regarding the process and the operation because the precise definition of these two terms will define the understanding of the Takt as illustrated in figure 17. The process is associated with the segment where the raw material is converting to the final product going through different stages or processes done by different workers. On the other hand, the operation is referred to as the movement of the workers to deal with a variety of products or materials. This is also known as the operational program (Shingō, 1998).

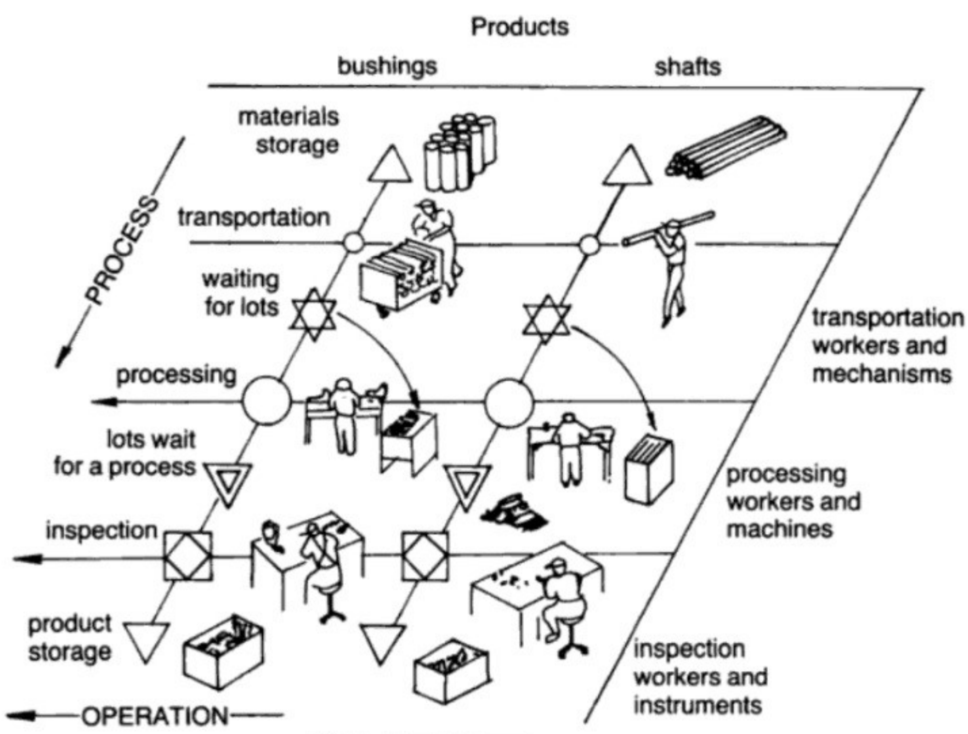


Figure 17: Shingo's two-way production system. (Shingō, 1998)

5.3 Takt Time Planning in construction

Takt in construction is a borrowed term from the manufacturing industry (Haghsheno et al., 2016). Though the authors agree that using Takt in a workstation designed from this methodology differs from adapting the workstation in a unique place and getting the same benefits, some resemblances can be recognized. Those similarities lay on different levels. The first similarity can be noticed between projects of the same typology, for instance, residential units, which will have a living room, bedroom, and toilets. The shape or the size of these similar areas can be comparable with the new designs of the automotive companies. (Frandson et al., 2013) states another similarity between construction and TPS, which is the repetitive activities, or the repetitive processes of completion in between different floors. The author identifies that interior construction activities offer more repetitiveness and Takt areas.

5.3.1 Defining Takt in construction projects

Construction projects consist of different stages, and they are delivered in a logically structured way of various activities (Clough et al., 2000). Those activities, depending on their nature, have different duration and technical specifications and restrictions. Integrating Takt into these activities will mean that all the durations for each work sequence will be even, and the sum of these sequences should not exceed the time terms planned in the construction master schedule (Frandson et al., 2013).

Frandson et al. (2013) quote Tommelein et al. (1999) when describing the intention of Takt in construction as the tool to create the so-called “The Parade of Trades” process, to meet the demand rate. In “The Parade of Trades”, as illustrated in figure 18, consists of a sequence of repeated activities, and each crew will repeat the same activity in different locations (Tommelein et al., 1999).

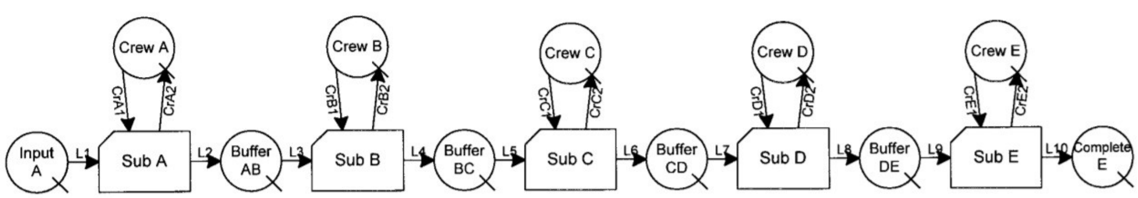


Figure 18: The Parade of Trades. (Tommelein et al., 1999)

Defining Takt in construction projects, analysis for all the work sequence and duration, broken into a detailed structure, is needed (Haghsheno et al., 2016). Based on this structure, the location for each process is assigned. The same processes, or work packages, which will repeat in different comparable locations in the same sequence, can be further analyzed to assess the possibility of time synchronization (Frandson et al., 2013; Haghsheno et al., 2016)

Balancing the time duration between the activities of the working packages will highly depend on the slowest process (Frandson et al., 2013; Haghsheno et al., 2016). This means that the other processes that might be faster will need to adapt their pace to the slowest one, compromising eventually the time terms planned in the master schedule. On the other hand, if the system is not balanced, then there will be a lot of time waste due to overproduction and financial wastes due to underproduction. The focus, therefore, is to improve the slowest activities and align the other activities with the pace of the slowest one.

The synchronization, according to Frandson et al. (2013), is mainly done by adding or removing the resources available for a particular activity. The optimum completion time for a "working package" can be defined in two ways. The first way is to set the time frames, which indicate the demand rate, and adjust all the processes in terms of resources and working methodology to achieve this milestone. The second alternative is to identify all the resources available, improve the composition of the crews, and the completion time will be as a result of the sum of the completion time of all the processes (Frandson et al., 2013).

The second perspective of alignment in terms of time should also be the location size, or the Takt area (Frandson et al., 2013). The repeating zones are a matter of architectural composition. However, integrating the Takt would require the same time duration for each repeated activities, no matter the size of the location. This was the trades will be composed to move through the defined Takt areas, or the physical areas, according to the schedule, creating this way a harmonious production system. Finding the final balance for the combination of the activity pace and activity's quantity is a back and forth process. The whole process itself is considered to improve itself, as trades will familiarize themselves with the means (Frandson et al., 2013).

The selection of the Takt time process is illustrated in figure 19. In the example that Frandson et al. (2013) describes, presented in this picture, there are identified five activities, which will be carried on by different working crews in four other areas. Theoretically, the completion time varies based on the volume of each activity, which will lead to waiting times for the crews. In this case, the Takt would be dictated by the slowest activities, specifically by the activity carried on by the trade one.

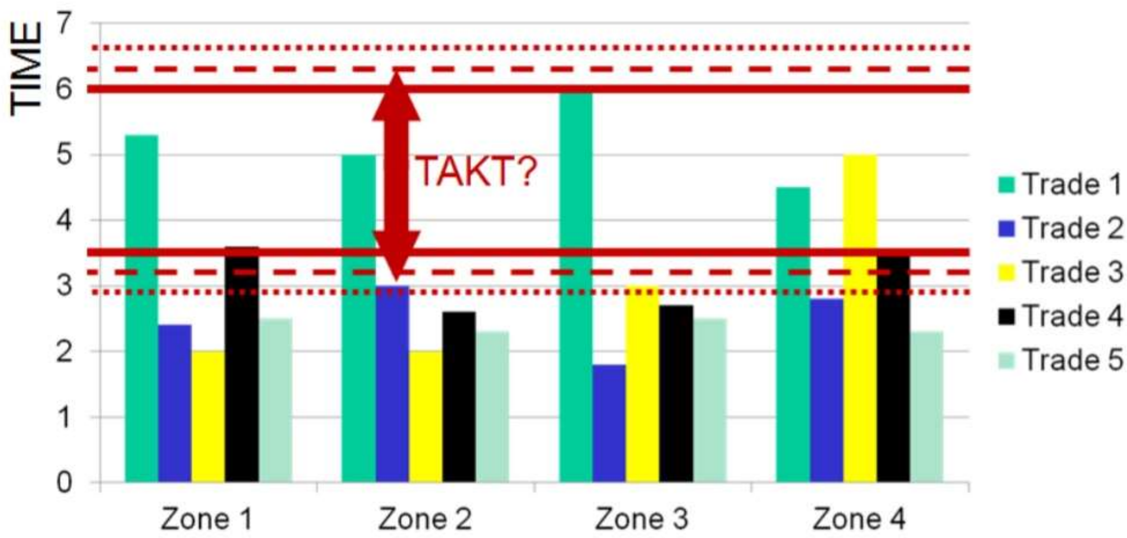


Figure 19: Defining the Takt time for different activities of the same working package in different locations. (Frandson et al., 2013)

Based on this graph, the average of each activity to complete should be defined, which means the completion time, which most of the activities tend to require. Theoretically, this will be Takt time, and the pace for each activity should be aligned with this duration time. This is done in this case by improving the speed of the slowest activity by adding more workers. As Frandson et al. explain, this will be based on the design, and an analysis of the working zone to assess the efficiency of the additional crews should be made. The assessment will define the feasibility of increasing or decreasing the pace of a specific activity (Frandson et al., 2013).

Haghsheno et al. (2016) illustrate a practical example of how Takt time in construction projects is defined. The authors agree that an entire team of professionals from different fields is required to conduct a Takt plan. Moreover, the collaboration of the supervisors of different executing teams, which agree on the composition of their teams, and commit to the plan. The commitment should be done by understanding the importance of schedule development and their responsibilities (Haghsheno et al., 2016).

Frandson et al. (2013), through different case studies, concluded into six stages process for the identification of the Takt time and its implementation into the production plan. The authors, however, agree that the steps depend on different kind of projects and their respective implementation challenges. The stages, according to Frandson et al. (2013), include as following:

1. **Collect the data from the Schedule**. All the information regarding the sequences, location, and planned resources is extracted and analyzed in this stage. Usually, the sequences are highlighted in the plan with different colors to distinguish them and help in creating a general idea of the production plans' duration.
2. **Identify the areas.** These areas consist of the zones where different trades will be allocated to implement the same sequence. Ideally, the size of these zones would be comparable, so the work completion duration for each zone will not have considerable alteration.
3. **Recognize the trade order.** This stage requires a lot of coordination between the participants, including different specialists. The sequence of the trades should be detailed and structured in a way that the whole processes, sub-processes, and the physical constraints (regarding the state of the materials) will be tangible.
4. **Synchronize the Workflow.** The synchronization for all the activities of the same working package in different locations consists of slowing down the fast activities and speeding up the slowest one to comply with the assigned Takt. The analysis for this stage is prepared, as explained in figure 19.
5. **Assess all the trade duration adjustments.** A reliable balancing of the workflow will require the assessment for all the done adjustments. In other words, this means that the theoretical Takt trade size assigned to reach a required production time will have to comply with the characteristics and nature of each activity. This means that the decision in the earlier stage, to increase or decrease the number of laborers, should be assessed by the specialists regarding its feasibility. This stage is vital in establishing the Takt time.
6. **Takt time plan.** A plan for the sequences, the location, and the zone order is generated. This plan is not only used to organize the trades and assess the implementation. At the same time, it enables immediate corrective actions if it is expected that the Takt time for a certain activity will not be met. In tight plans

like Takt time, the decisions should be made immediately as a massive chain delay might occur.

Different researches link Takt-Time Planning with the Last Planner System and Location-Based Management System, which will be further discussed in the other chapters of this thesis.

5.3.2 Takt Schedule

As described in other chapters, in broad terms, a Takt-Time Plan is a result of the combination of three main factors: (1) sequence; (2) location; (3) Levelling of resources to define the Takt (Frandson et al., 2013; Haghsheno et al., 2016).

Ideally, a TTP would look like the Parade of trades that Tommelein et al. (1999) describe, as illustrated in figure 20. However, in construction, due to the high complexity and the unique character that each project has, it is difficult reaching that schedule perfectionism (Frandson et al., 2013). Therefore, the duration of each process of the sequence should also include some buffers at the end of every task.

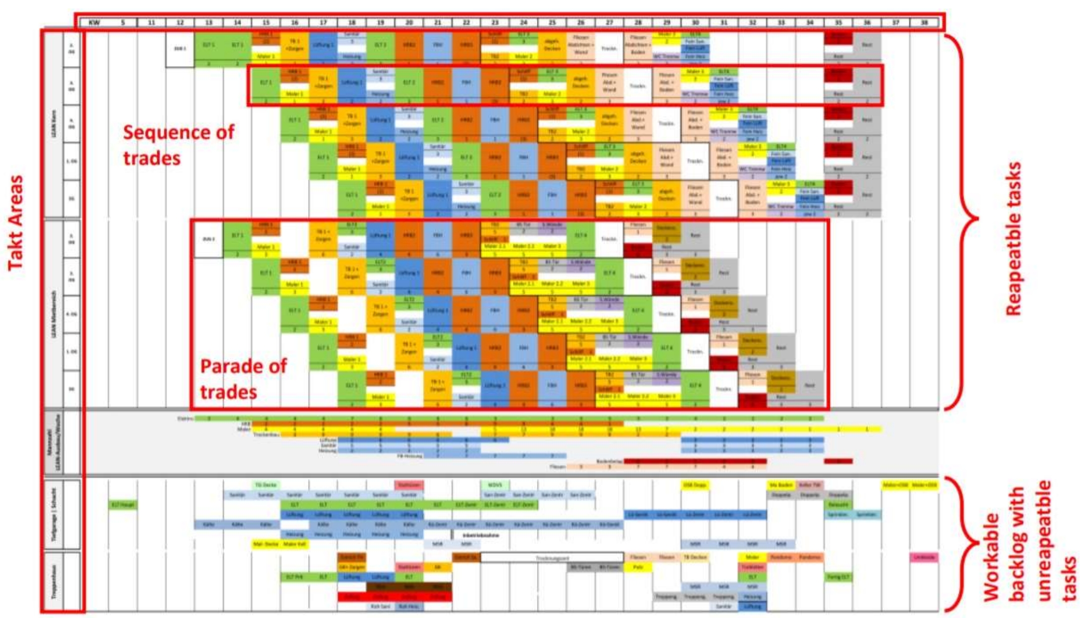


Figure 20: Takt-Time Plan. (Haghsheno et al., 2016)

Haghsheno et al. (2016) refer to a Takt plan as a repeated train wagon. The train wagon is the sequence. The authors quote Hamzeh et al. (2008, pp 641) when stating that the activities and sequences that are non-repeatable or are not considered relevant to be Takted should also be illustrated in the Takt-plan, including their location and implementation duration (in figure 20 indicated as ‘Workable backlog with unrepeatable tasks). For the illustration of a TTP, authors do not suggest the tools that do not show the location as the Takt-zone is vital in indicating the resource allocation process and the task completion time (Haghsheno et al., 2016).

5.3.3 Takt Control

A Takt-Time Plan is a tight schedule, thus controlling its development in between Takts and taking corrective actions before the delay exceeds the Takt is critical for its further implementation (Frandson et al., 2015; Gardarsson et al., 2019; Haghsheno et al., 2016). Controlling actions should be forecasted in the planning phase by integrating some buffers, and most importantly, all the participants should be aware of chirurgical nature that implementation of Takt has (Frandson et al., 2013, 2014). This means that the participants should commit by assessing their resource capabilities in doing the work in the planned time frames.

However, the construction industry presents many unforeseeable situations (Frandson et al., 2015). As the authors state, if a trade cannot deliver the activity in time and no countermeasure is taken at the right time to avoid it, then the plan will face the domino effect. In some cases, different zones might face unique implementation challenges that were not anticipated in the schedule. In this case, the authors propose that this zone should be left out of the Takt plan, and the trades should continue in different Takt zones. As the Takt plan is conceptualized to go always under improvements (Shingō, 1998) with the TPS), the problems during implementation should be analyzed, and measures should be taken in time to avoid the plan failure (Frandson et al., 2015).

Haghsheno et al. (2016) introduce the term “Shopfloor Management” when explaining the controlling structures that a Takt implementation requires. The authors describe that a Takt Control Board and all the individual supervisor of the crews are part of the managing and controlling the plan. Based on the Takt-Time, regular meetings are held on a time basis, with broad participation from all the participants. In those meetings, all the documented information by the Control Board is displayed, and corrective measures are taken collaboratively (Haghsheno et al., 2016).

The documentation procedure is a critical task from the Control Board (Frandson et al., 2014). Binninger, Dlouhy, Haghsheno (2017) describe that the information should be accessible from all the participants, so their integration into the decision-making process is enhanced. Therefore, the Control Board, as Binninger et al. (2017) explains, focuses on recording the following information:

1. Trade composition including the total number per crew
2. Machinery used for implementation
3. Progress rate and compliance with the plan
4. Different defects
5. Records related to the site safety
6. Interruptions of work for different reasons
7. Information regarding the organization aspect of each crew and preparing the Takt is for the next crew.

Though Frandson et al. (2015) describe a Takt-Plan as unique for each project, and each project should develop its Takted plan independently from other projects, Binninger et al. (2017a) agrees that the data gathered from the Takt Control of one project can be adapted and utilized in developing a Takt-Time Plan for another project. Therefore, accurate documentation can be considered a database for future Takt-Time plans (Binninger, Dlouhy, Haghsheno, 2017).

5.4 Takt Time Planning as a work structuring method

Work structuring, according to Ballard (2000b), is the structure of all the construction processes, in combination with the design requirements, supply chain, and all the necessary input to deliver a reliable production system. Tsao (2005), in her dissertation, defines the work structure as a structured way for the deliverables of projects to meet customer expectations and needs.

Tsao's dissertation illustrated many findings regarding productivity in project-based production. Project-based construction, according to Tsao et al. (2000); Tsao (2005), and Ballard (2000b), is considered those construction projects which are based on contracting the works to other parties. So the subcontractors and workers are hired based on specific projects. The findings associated with productivity improvement that Tsao presented include almost all the phases of a construction project lifetime. She highlighted that the design proposal itself defines the means of delivery. Moreover, she quoted Shingo (1998) over the productivity improvements of the project due to the upstream operations, and the contracts increase the commitment of the different project participants enabling this was a more structured project delivery.

The findings that Tsao introduced were the foundation of (Frandson, 2019) dissertation to present an in-depth work structuring method for Takt Time Planning. Frandson quotes Ballard and Howell (2003) when recognizing that Takt Time is a structuring method and that during the conceptual phase of each project, there should be defined clearly the duration in time of when this project **can** be implemented and the term when **should** be implemented. This analysis is done in order to find means and methods to deliver the project based on the demand. For this purpose, the project should be analyzed at a task level, sequence level, and phase level (Frandson, 2019)

As mentioned in the other chapters, the Takt Time imposes the same duration for each activity. Frandson (2019) simplifies his research into different phases of construction. Therefore, the same analysis that is done to define the Takt for a group of activities is also done for each phase of construction. This means that a work breakdown structure to determine the main stages of construction should be done. As Frandson describes, the duration of each phase should be set, so the overall duration of the project will meet the customer demand in terms of time. A breakdown structure should also be defined for the location of the activities for each phase; then, the Takt should be defined as described in the other chapters of this thesis.

Frandson (2019) matches his TTP structure concept with the “Lean Project Delivery System, LPDS” (figure 21) that Ballard and Howell (2003) describe. This thesis will focus more on the gaps regarding the “Lean Design” phase of LPDS and try to integrate this phase on the project scope phase, which is usually defined by the designers. Usually, in a traditional way, the scope of the project stays static, and all the methodologies and the means should align to deliver the scope. This is not the case in Lean Design, which allows flexibility on the scope (Ballard and Howell, 2003).

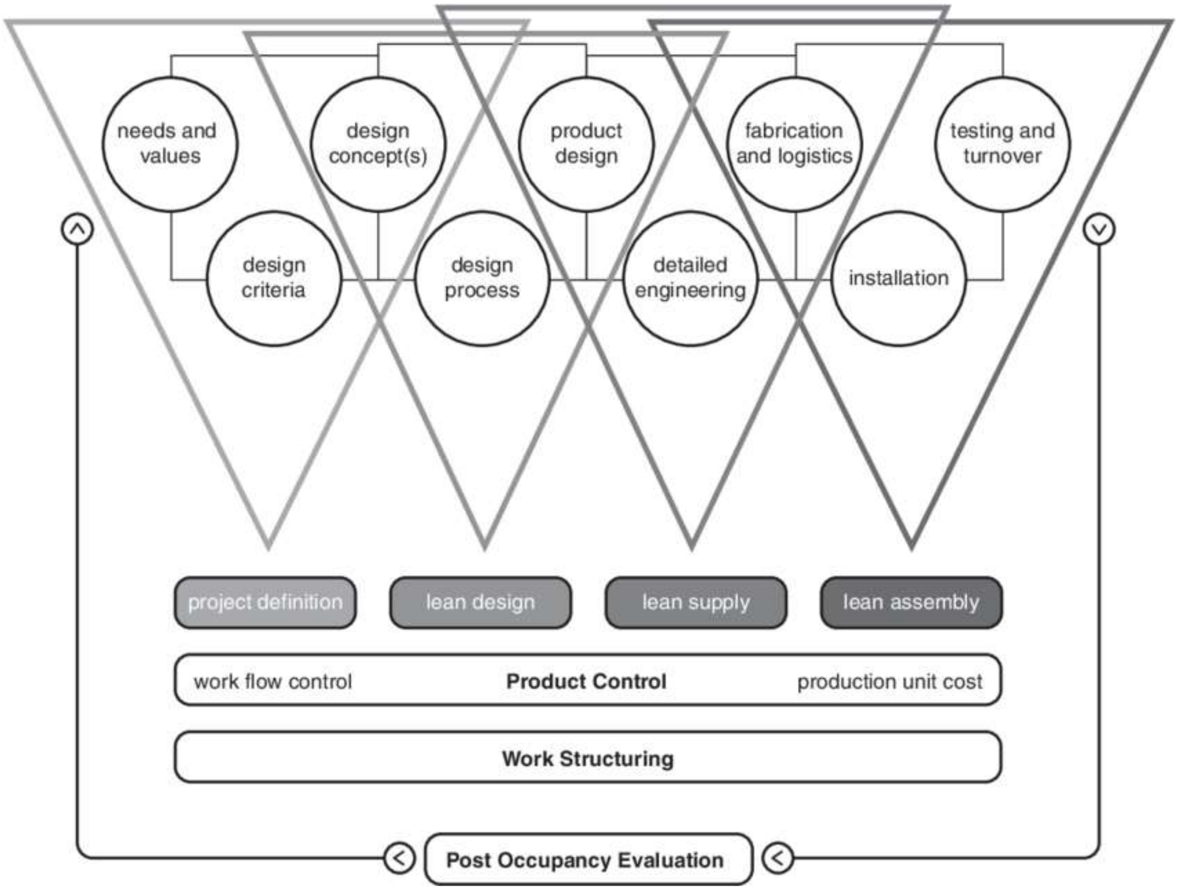


Figure 21: Triads of Lean Project Delivery System, LPDS. (Ballard and Howell, 2003)

5.5 Drafting a Takt Time Plan

Following the Lean Principles in the Lean Design Stage of the Triads of Lean and using TTP as a work structuring method will generate a massive plan that will be difficult to read for the participants, especially on large scale projects (Statsbygg, 2017b). As different studies imply (Binninger, Dlouhy, Haghsheno, 2017; Frandson et al., 2013; Haghsheno et al., 2016), various activities of the same sequence are indicated with different colors, and this sequence is repeated in all the Takt zones, as shown in figure 22.

Figure 22 represents a Takt Time Plan for a sequence of activities. On the first two columns on the left, it is respectively indicated the floor where this sequence is happening and the specific Takt zone in relation to the particular floor. The horizontal direction of the plan suggests the duration of each activity of the sequence and the order at the same time (Linnik et al., 2013).

Figure 22: Takt time plan format. (Linnik et al., 2013)

However, different construction companies have different ways of illustrating Takt plans in complex projects. Binninger, Dlouhy, Haghsheno (2017) introduce a presentation of a Takt schedule as a train with wagons. In this case, the train represents the sequence, and the wagons "carry" the information about sub-processes. Wagons have different colors to indicate that the group of activities is diverse. Simultaneously, the waiting time is marked with an empty wagon (Binninger, Dlouhy, Haghsheno, 2017).

The train schedule that Binninger, Dlouhy, Haghsheno (2017) illustrate has the same principles as to what (Haghsheno et al., 2016) proposed (described in subchapter 5.3.3, refer figure 20), which is the integration of those activities which are not part of the Takt in the schedule. In the "train" of figure 23, Binninger illustrates the integration of non-Takted activities in the schedule to see the overall development of the project indicate the location for each activity that is progressing on site.

However, depending on the Takt, different visualization is used for different schedules. Other planners differentiate the location by using different codes and colors (Brioso et al., 2017). The information regarding the location is explained in a legend attached to the schedule. A map indicating the zones should also be accessible to the participants, so the movement of the working trades will transparent to avoid any inconvenience.

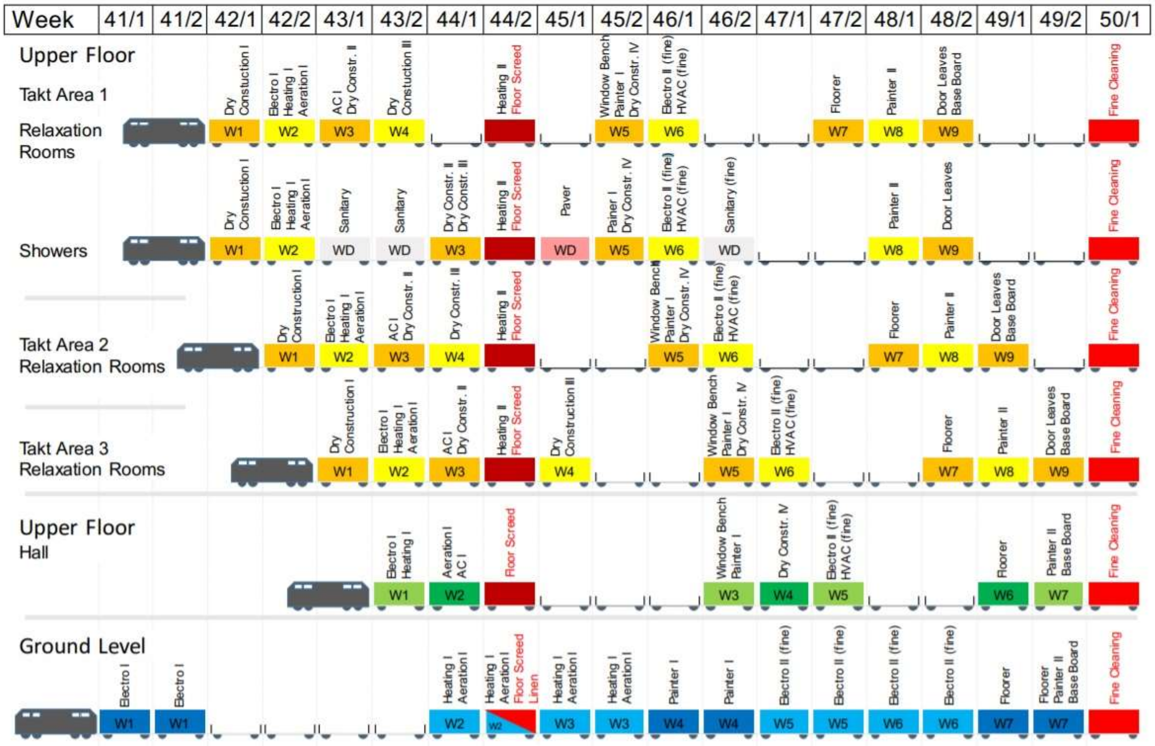


Figure 23: Takt Time Plan, train visualization. (Binninger, Dlouhy, Haghsheno, 2017)

In the example illustrated in figure 24, extracted from Brioso et al. (2017) comparison of three different scheduling techniques, the Takt for each structural sequence is planned one day. The exact quantities were not described. However, a reinforcement plan divided into four sections was available. From the schedule, “Z” indicates the zone in the reinforcement plan, and “S” indicates the level (story) (Brioso et al., 2017). The movement of each trade of the sequence is indicated by the different colors of locations. The specific duration for each sub-process is not defined.

TAKT-TIME 4 ZONES															
DAYS	Mon	Tue	Wed	Thu	Fri	Mon	Tue	Wed	Thu	Fri	Mon	Tue	Wed	Thu	Fri
	1	2	3	4	5	8	9	10	11	12	15	16	17	18	19
TASKS															
Structuring Phase															
Vertical Rebar	Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3			
Vertical Piping Installation	Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3			
Vertical Electrical Installation	Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3			
Vertical Formwork	Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3			
Vertical Concrete Pouring	Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3			
Horizontal Formwork		Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3		
Horizontal Rebar		Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3		
Horizonal Piping Installation			Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3	
Horizontal Electrical Installation			Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3	
Horizontal Concrete Puring				Z1-S1	Z2-S1	Z3-S1	Z4-S1	Z1-S2	Z2-S2	Z3-S2	Z4-S2	Z1-S3	Z2-S3	Z3-S3	Z4-S3

Figure 24: Takt schedule for structural activities. (Brioso et al., 2017)

5.6 Advantages of using Takt Time Planning

The use of TTP as a work structuring tool provides many advantages in terms of duration and costs (Linnik et al., 2013). Different researches using case studies to implement Takt Time planning (Frandson et al., 2013, 2014; Frandson et al., 2015; Haghsheno et al., 2016; Heinonen and Seppänen, 2016; Linnik et al., 2013; Millstein and Martinich, 2014) highlight the effect that Takt Time has on the overall project delivering, by decreasing the implementation time while maintaining the same quality. Though Linnik et al. (2013) state that there might be losses in the overall capacity, Frandson et al. (2015) state that overall the crew's size is reduced. This happens because the activity that plays the bottleneck's role will slow down other activities that are faster. Eventually, reaching the Takt set for fast activities will reduce the number of laborers per crew.

Haghsheno et al. (2016) state that planning a tight schedule will reduce the buffers between dependent activities and will implement the Just-in-Time principle for the deliverables. According to the authors, this is done by fully integrating the supply chain into the plan. The main reason behind this is to improve the onsite material storage, as it is critical for the crews allocated in different Takt zones. Moreover, performing the same activity consistently improves the process itself, as the crews familiarize with the project, and the tasks will increase the production rates. This will increase the reliability of the teams (Haghsheno et al., 2016).

Moreover, as explained in the sub-chapter 5.3.3, the effectiveness of controlling and the on-site synchronization of the so-called "Shopfloor Management", combined with the implementation of the participants in the decision making, will deliver a high-quality product (Haghsheno et al., 2016). On the other hand, less research is done on the financial aspect of Takt Time. However, Linnik et al. (2013) imply that implementing TTP in construction decreases project costs. The authors illustrate with a diagram the advantages of using Takt Time, presented in figure 25.

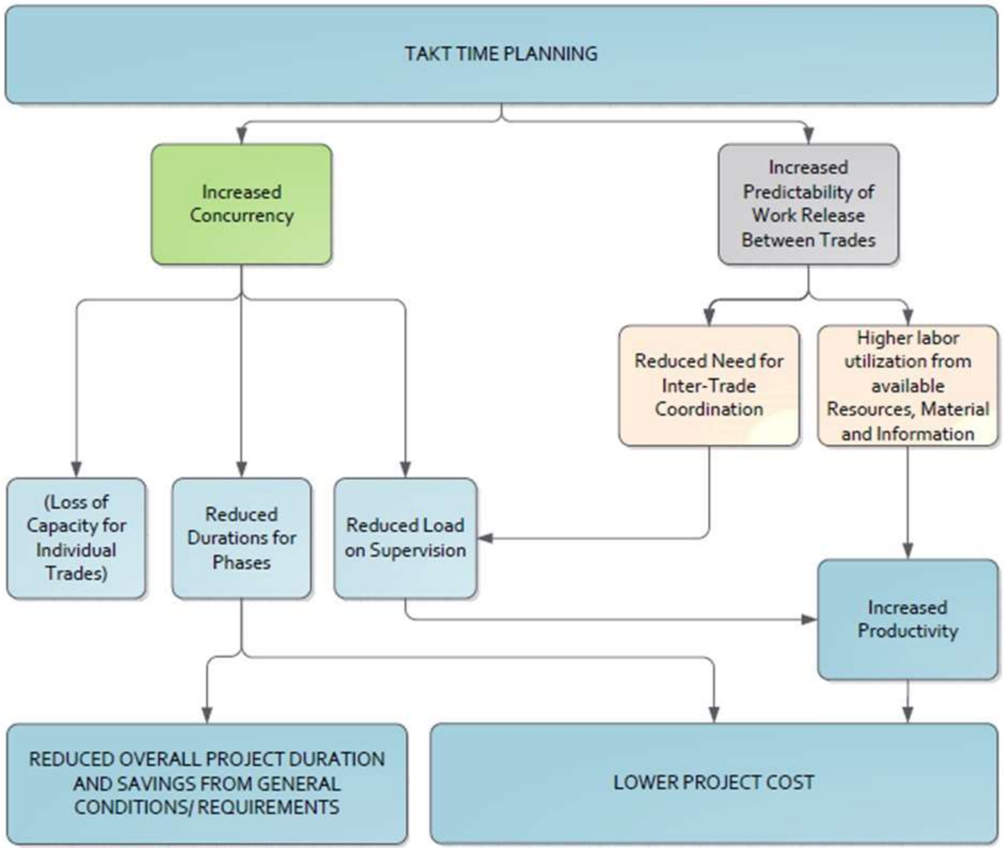


Figure 25: Benefits of using TTP in construction. (Linnik et al., 2013)

Another research conducted by Frandson et al. (2013) includes the financial aspect of the project in terms of cash flow. The authors state that producing a detailed plan and calculating the exact productivity of all the trades enable adjusting the cash flow of the project and, at the same time controlling the daily costs. In other words, Takt Time planning can generate balanced cash flow and also prevent cost overruns (Frandson et al., 2013).

5.7 Complements with Last Planner System™

For the implementation of a project that uses Takt Time as a work structure tool, the Last Planner System (LPS) is used for controlling and integrating the broad participation of the individuals who execute the work (Frandson et al., 2014). The authors use a case study project to describe the alignment of two tools to augment the values of each other. In this case study, Takt Time Planning is used for the interior works. The authors found that the two tools are complementary in many perspectives. In broad terms, they concluded that TTP extends LPS to the constant and homogenous workflow, and LPS delivers the instrument to control TTP implementation.

Through the results of this case study, Frandson et al. (2014) stated that TTP facilitates the LPS in many ways. According to the authors, by providing an exact sequence of activities and a Takt duration, the focus of LPS is centralized in committing to reach the Takt rather than planning the upcoming sequence. This approach sets a clear target for the executors. However, as the authors state, there is the risk that the pressure for certain trades might increase in the case they do not possess the right physical capabilities to reach the Takt.

Moreover, the collaboration between the working trades is improved, as the whole team involves and contributes to an ordinary resolution (Frandson et al., 2014). The authors quote Koskela’s flow while explaining the importance that teamwork has to production. Every trade on site knows the daily production target and all the coordinated information regarding their future allocation, which leads to a diminished scope of the lookahead process (Frandson et al., 2014).

The last complement of TTP is the differentiation that TTP does between “schedule noise” and “schedule variation”. The first one is similar to the float, which means that if a task of a specific sequence shifts, it will not affect the overall duration of the Takt sequence. The “schedule variation” is the movement of a task from one sequence to another (Frandson et al., 2014). According to the authors, this differentiation will reduce the risk of the plan, and at the same time, it resolves many micromanagement issues and it improves the LPS.

On the other hand, LPS regulates the TTP variances by developing the collaboration process (Frandson, 2019). The variations are regulated by engaging the workers of each crew in the decision process. At the same time, according to the author, LPS fills the gap of TTP means and methods of controlling the implementation.

5.7.1 Last Planner System

Last Planner System is a lean tool that targets a broad participant involvement during the construction execution phase (Ballard, 2000a). According to the author, this tool enables collaboration between all the responsible individuals and specialists of different construction activities. Discussions are made on a timely basis, and more detailed planning is agreed from all the participants. The improved and agreed schedule should comply with the master schedule milestones, as it is the origin from where it is generated.

The first step of the LPS is to identify all the activities that need to be executed according to the master schedule (Ballard and Howell, 2003). The activity and the description of the scheduled work should be well defined and should contain the right logical sequence and the exact amount. In this way, the specific quantities will enable aligning the delivering and physical capacities of the executer with the workflow (Ballard, 2000a).

The second step is to assign the proper resources to the agreed work that will be done (Ballard and Howell, 2003). In this step, the supervisor of each executing crew defines the number of laborers that are needed to afford the load of work that is promised to be finished at a specific time under agreed conditions. This process is also known as the “Lookahead Process” because of the fact that regular meetings are held in order to detail the schedule and agree on how the work will be done, by who, and exactly when (Ballard, 2000a). The lookahead time can be decided upon by the participants. Usually, it is from one week to one month, and it depends on the nature of the work that needs to be carried

In the regular meeting, participants commit to doing the work agreed upon. This consists of the third step of LPS. The last planner is considered to be that individual or the crew that is involved directly with the work that will be done (Ballard, 2000a). The information over responsibilities, time terms that have to be respected, and the linkage with other processes is shared and agreed upon over all the involved participants in a very transparent process. According to Ballard and Howell (2003), the commitment of the Last Planner should be made under four criteria: (1) definition, (2) quantity, (3) logical order, and (4) improvements during the process (Ballard and Howell, 2003).

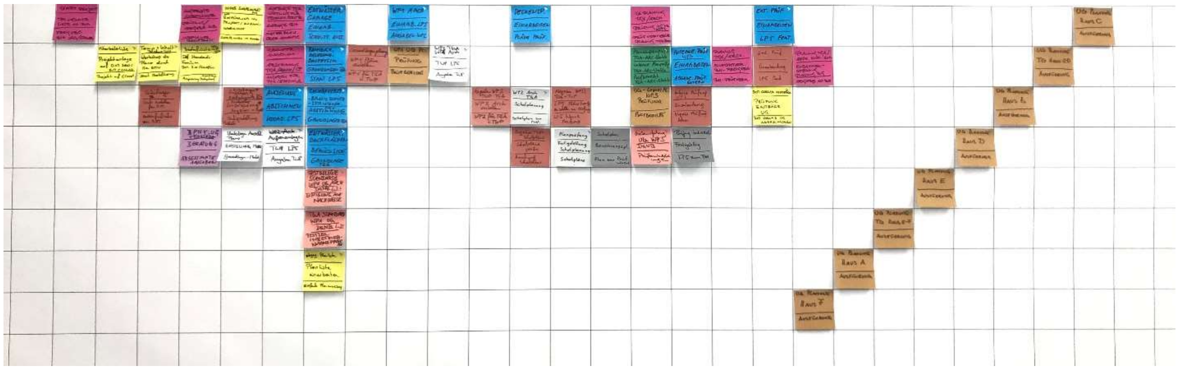


Figure 26: The Last Planner System, planning board. (Refine Projects, 2019)

Summarizing, as illustrated in figure 26, during the “commitment” meetings, the participants decide when they will do the work that should be done. Every participant has a different colored paper, and they stick it on the planning board. This is also known to be a reliable commitment (Ballard and Howell, 2003). However, the final decisions are made in collaboration between all the participants.

In contrast with the traditional construction management tools, LPS is a pull methodology (Ballard, 2000a). This means that not only the time targets are to be met, but a comprehensive aspect should also be taken into consideration to eliminate all kinds of wastes. Practically, the pull concept in LPS consists of introducing the supply chain in the planning process and enabling all the participants to decide when they will do the work that needs to be done.

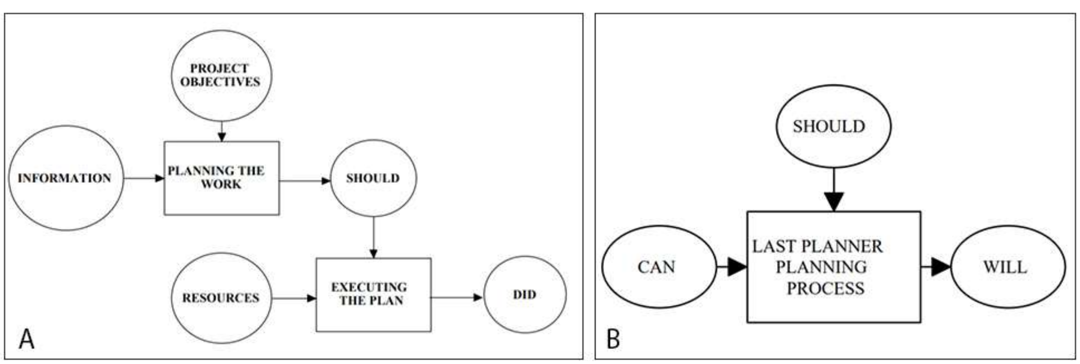


Figure 27: Comparison between push strategy (A) and pull strategy (B). (Ballard, 2000a)

5.8 Complements with Location-Based Management System

Frandson et al. (2015) conducted research to highlight the similarities and differences between the two methodologies. The authors agreed that the two methods have more similarities as they are both based on the location of the activity and aim to create a continuous workflow. Besides the equal duration for each activity, the TTP location is more precise as it breaks the location of the same floor into the so-called Takt areas. Therefore, the allocation of the resources on the same level is more concise, which strictly disciplines the movement of the crews. This means that the visualization of each schedule is done in different ways (described in the respective chapters of this master thesis) (Frandson et al., 2015).

Another difference is the buffers used on each planning methodology (Frandson et al., 2015). Two methods, as the author state, use the space buffer similarly and the empty wagons due to workability constrain (dry time, etc.). The LBMS, beside the space buffer, uses the time buffer as well, while in TTP, the time buffer is indicated by the wagons that Linnik et al. (2013) explain. In other words, the duration of a Takt can also be considered as a time or space buffer, as a Takt contains information for the duration and the location. On the other hand, as Frandson et al. (2015) implies, in contrast with LBMS, the capacity buffer is widely used in TTP for two main reasons: (1) to regulate the Takt time; (2) to organize the foreman on the same level efficiently. Resource usage indicates another fundamental differentiation between the two methods. While LBMS aims to use the resources based on the target for each activity, TTP underload the resource usage in regards to the Takt that the bottleneck activity enforces.

The main contrast that the two methods have is control methodology and means (Frandson et al., 2015). The authors highlight the structure of monitoring and the time span of taking corrective actions. In LBMS, there is a hierarchical structure of site engineers that monitor the progress, and the corrective measures are taken collaboratively between the same network. The TTP the hierarchy is flatter, and all the participants play a role in reporting the progress and contributing to decision-making. The space break down structure is advantageous in TTP for indicating the exact location where the problem arises, but the correcting time is very tight, in comparison with LBMS, which allows more flexibility (Frandson et al., 2015).

5.9 Complements with Building Information Modelling

Less research is done over the linkage of Takt-Time Planning and Building Information Modelling (BIM). Though there is a wide confirmation that both tools aim to increase the productivity and the efficiency of the construction processes (Melzner, 2019; Sacks et al., 2010), there is not a clear framework for incorporating the two tools.

Sacks et al. (2010) research over the interaction of Lean and BIM listed fifty-six inter-connections between the two tools. However, the authors also described why the current technologies do not create a friendly environment for incorporating the two tools with each other in all the stages of the construction. Difficulties appear to be more in the embracement of the two tools combined rather than individually. The authors describe that most of the companies are on a learning stage for each of the tools separately, and there is a gap between the theoretical development of the two tools and the practical implementation of construction stages. However, they do agree that depending on the required benefits. A parallel implementation can be done in some segments of the construction lifetime (Sacks et al., 2010).

In the research of Sacks et al. (2010), the two tools are considered as separate disciplines that are used to improve the production theory (figure 28). According to the authors, construction companies use the two tools in different stages, though the target of each one is the same. They describe the usage of BIM on the design stage and Lean in the implementation phase. The parallel activity of each one is crossed at some point in the back-and-forth process of design and implementation strategy. Moreover, the management team uses the data generated by BIM models for accurate quantity take-offs, cost estimation, and better visualization of the schedule. In this research, there is not defined specifically TTP as a work structuring model. However, the authors do agree that BIM is used to visualize 4D schedules (Sacks et al., 2010).

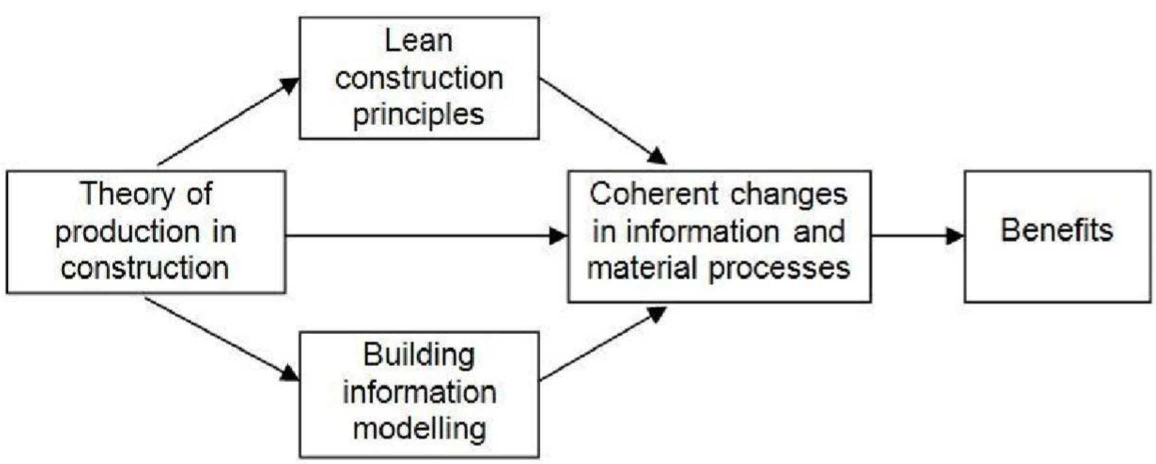
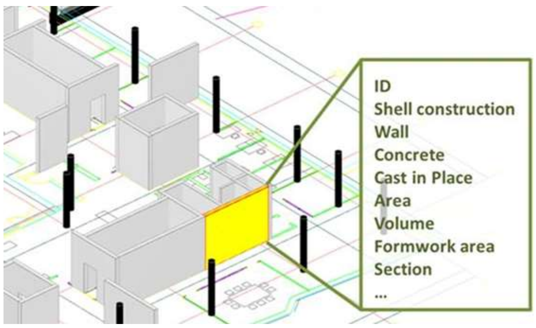


Figure 28: The usage of Lean and BIM to improve productivity. (Sacks et al., 2010)

The first attempt to incorporate TTP in BIM was made by Melzner (2019), which developed a TTP in a BIM model for repetitive activities. The input that a BIM model needs to generate a TTP schedule is also analyzed. In the case study that the author explains, it is not well defined whether the process is entirely BIM, or it also includes manual adjustments. However, the attributes that a model needs to generate a 4D Takt schedule are clearly defined. It contains detailed specifications for each component of the model, including the location and the sequence number (figure 29). The input for each building component should be included in the design phase (Melzner, 2019).



Attributes	Attributes
ID	Ceiling surfaces
Component type	Floor area
Classification	Floor
Room number	Construction phase
Length, Width, Height	Takt number
Ceiling height	Process code
Structural height	Costing code
Wall surfaces	

Figure 29: The list of attributes that each component of the building should have. (Melzner, 2019)

This case study uses an accurate 3d model, including the hierarchy of the activities and exact quantities. The framework for Takt implementation that Melzner used consisted of eight steps:

1. Defining the lowest Takt zone for repetitive activities
2. Identifying the trades
3. Identifying the WBS
4. Assign the number of labors per trade
5. Takt calculation
6. Extract the sequences
7. Determine the construction interdependencies
8. Takt synchronization

The author's strategy is limited by the fact that the project has a high repetitiveness factor. Therefore, the steps he followed are done for interior works of one floor, then the schedule is repeated automatically for all the floors. The author developed an accurate Takt schedule for the framework construction, which is illustrated in figure 30 ("W1 – concrete walls, SL1 – concrete slabs"). The duration and the production rate of the model, as the author describes, will be the foundation input, combined with the accurate quantities that a BIM model provides, to determine the number of labor.

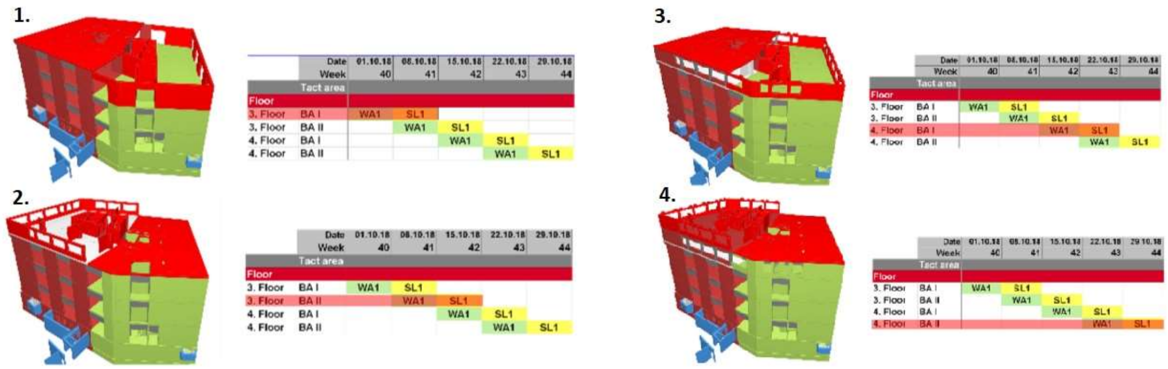


Figure 30: 4D Takt schedule for framework construction. (Melzner, 2019)

However, Melzner emphasizes the fact that in order to develop these kinds of schedules, in-depth knowledge over construction development structure and awareness for certain decisions is needed. Also, the feasibility of developing such plans should be assessed in terms of time and costs (Melzner, 2019).

6. Case Studies

In this chapter, three case studies that integrate Takt-Time Planning as a scheduling technique will be introduced. The focus of these case studies will be on TTP's process steps, the role of participants, and preconditions of integrating it. Moreover, each case's objectives will be articulated and will provide the basis of a comparison between the used approaches.

6.1 Bergen Academy of Art & Design – KHiB

This case study is extracted by the booklets of the project, prepared by the main project actors, namely: Hans Thomas Holm – Head of the Project (Statsbygg); Astrid Renata Van Veen – Project Manager ARCH (Snøhetta); Sven Wertebach – Project Manager Design (Atkins Norway); Per Roger Johansen – Project Manager Production & Systematic Completion (Atkins Norway). Officially this project is known as "Faculty of Fine Art, Music and Design (Kunst Musikk Design - KMD)." Still, in this thesis, the author will refer to KHiB as the project was designed to replace the old "Bergen Academy of Art & Design," and was mentioned as KHiB project until the 1st of January 2017.

6.1.1 Introduction

This project, designed by the renowned Norwegian architectural firm Snøhetta, is located in Bergen, Norway. The winner of the competition of designing KHiB was assigned in 2005, but the facility was opened in 2017. The building is organized in a total area of 14 800 m^2 organized in four levels (Snøhetta, 2017). A table with the main data of the project is presented below.

Type of Contract	Design-Bid-Build
Client	Statsbygg
Architects	Snøhetta
Project Management	Atkins Norway
Project Consultants	Rambøll
Lean Consultants	Porsche Consulting
Project cost	1 B NOK (£ 100 m)
Duration of construction	22 months

Total number of contractors	11
Number of tested systems	200

Table 2: Project descriptive data. (Statsbygg, 2017b)

6.1.2 Project timeline

The project ensured funding in June 2013, and the construction works started at the beginning of 2014. Lean thinking was a concept integrated since the early stages of the project. The project officially started with a kick-off meeting with the participation of the project team and the main stakeholders, including the end-users.

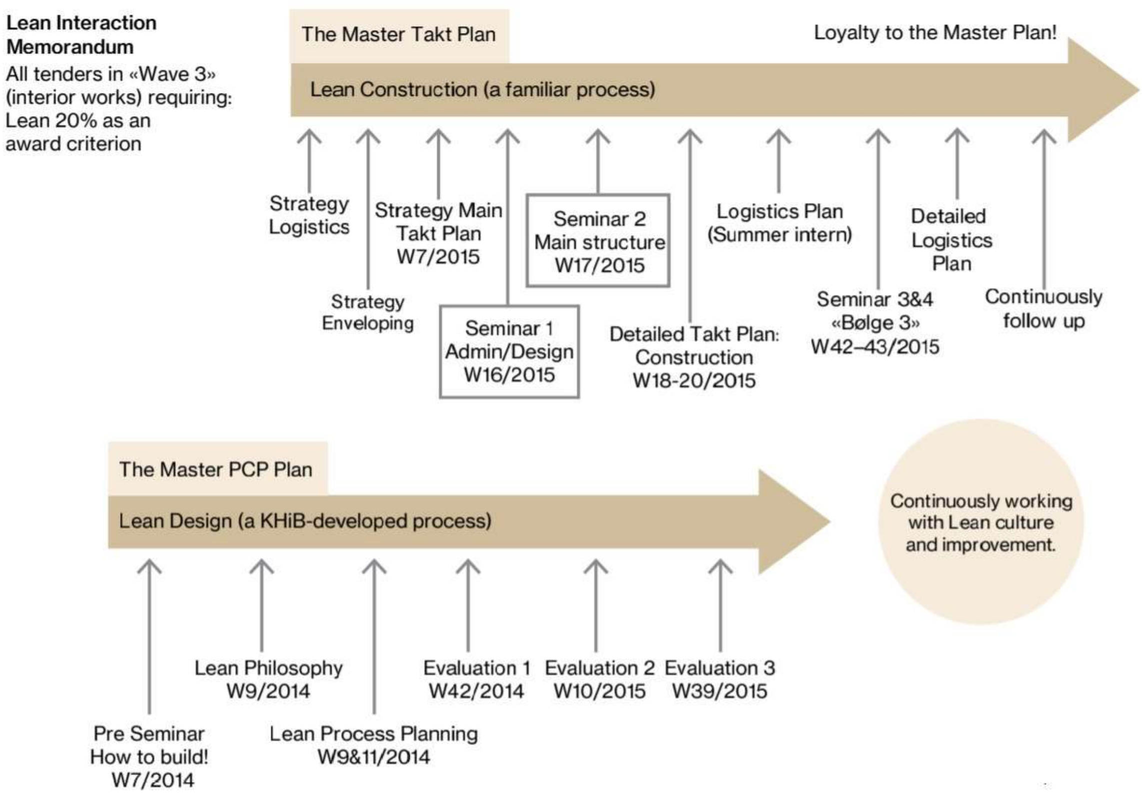


Table 3: Lean Strategy timeline (2013-2016). (Statsbygg, 2017c)

The initial goal of the project team was to determine the logic of how things will be done and set up the foundations for the Lean training as a significant number of the team members were not familiar with what the authors call the “Lean culture” and the Lean methodology. The training started in the 9th week of 2014 and continued through all the construction phases. A Takt plan, following the Master Plan’s milestones, was developed in the 7th week of 2015, which was shared with the contractors and detailed collaboratively from the 18th to 20th week of 2015. Meanwhile, the construction on site was continuing from the beginning of 2014. While the participants were detailing the Takt Plan for the interior works, the framework and the shell of the building were on-going.

6.1.3 BIM model and procurement

The client encouraged the use of BIM since the early stages of the project design. Therefore, the BIM model used in the design phase was later on used in production processes. The project team conceptualized the usage of the BIM model to create the desired construction flow with a Takt of seven days. The BIM model was used to create the necessary transparency, which enables everyone to know what the others are doing so everyone could adjust their pace. To achieve this, the team located six portable BIM kiosks, where everyone had access to retrieve information, specifications and check the status of other activities to avoid different trades working on the same location at the same time.

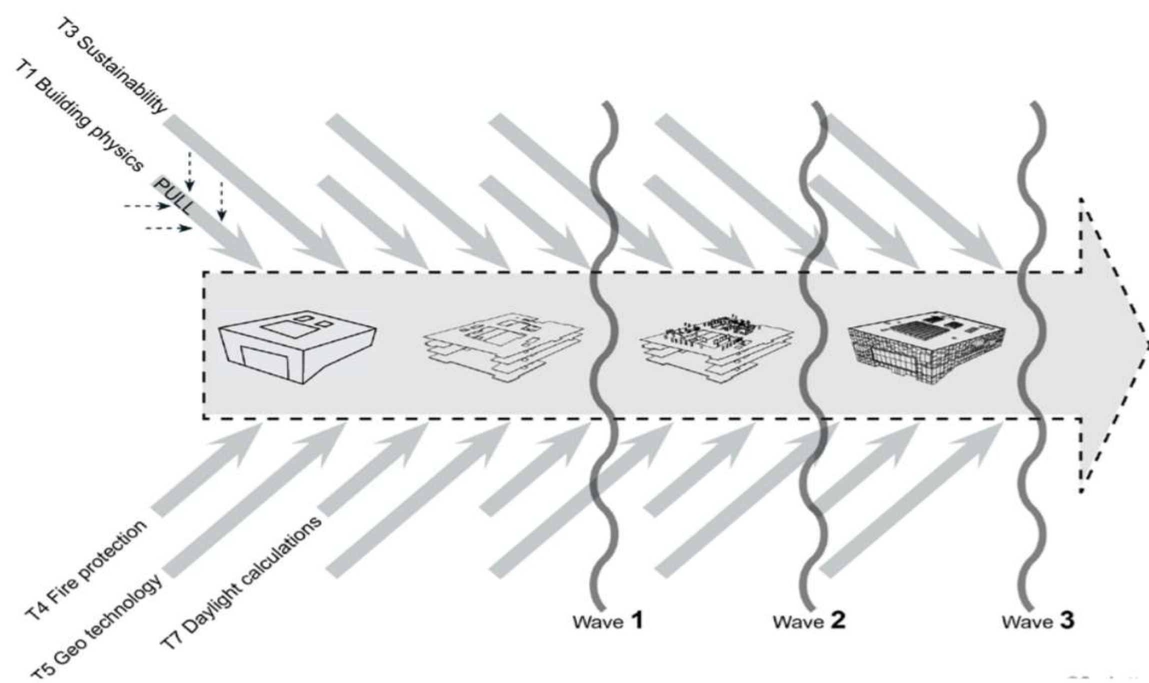


Figure 31: Detailing the BIM model and deliverable packages (wave 1,2,3). (Statsbygg, 2017b)

The project team considered the flow of the information very crucial. Therefore, the design phase was regarded as a production line. All the specialists were asked about the core of their systems, so it could not be negotiated or changed in the BIM model.

The idea was to create the BIM model "skeleton" that the respective specialist would decide what value-adding is and what level of detail they would provide. This process would happen collaboratively, so everyone was aware of the importance of each piece of systems and components. Moreover, changes would be done collaboratively to mitigate the process interaction, and relevant real-time information was enabled to the concrete engineers.

To ensure that the contractors had the necessary knowledge and commitment to deliver the project with Lean methodology, a specific criterion of 20 % Lean - based working was set in the tendering phase (wave 3), which made it easier for the project team to integrate their requirements. Moreover, an initial TTP was attached to the description of the tender, which was 80 % accurate regarding the detailed final TTP. This way, a collaboration between the project team and the contractors was essential for improving the schedule.

6.1.4 Takt-Time Plan

The central part of the schedule was arranged before the construction of interior works started in the Takt areas. The Takt plan is the KHiB project was prepared for all the interior activities. However, a long preparation was done beforehand, and defining the Takt Plan went through a system of steps 14-10-6-4-1, which indicate the weeks prior to construction. These are three main stages before the construction start that determined the TTP and the preparations for its integration. These stages are described below:

- **Preparing the production system.** This stage was done 14-10 weeks before the construction took place. Regular meetings between specialists of different disciplines were held to design the production system, which means to arrange all the dependencies and facilitate the interdisciplinary challenges. These meetings also arranged the activities that need to plan the supply chain in order to have the products in the required time on site.
- **Defining the production.** This step took place 6-4 weeks prior to construction on-site for each Takt area. From week 10-6 before the construction, the issues solved in the first step were drafted and prepared for the detailed Takt plan. Coordination between all the participants is needed in this step due to the high

level of detail. The collaborators in this phase are the contractors and the sub-contractors, and the site management. All the contractors are introduced to the project through a BIM model. Four weeks prior to construction, the contractors get to know virtually with the project. The software that used was Solibri. All the contractors and the subcontractors clarify every issue that arises, and for every chunk of activity, the solutions are discussed and decided. At the same time, meeting with the supply chain were held during this period of time. Having accurate quantities from the BIM model and knowing when different deliverables are needed on-site, the logistics were all organized four weeks in advance for each activity. In the KHiB project, the Logistics manager arranged all the meetings and discussions regarding the deliverables of contractors and subcontractors.

- **Ready to start.** In this stage, one week before the construction in any Takt area, the foremen participated in the informative meeting and were introduced to the TTP. A testing room was built on-site, so the project team could test if the Takt was defined realistically. This decision was crucial in maintaining the progress rate. The test room was in a real Takt area, and all the activities of the "Parade of Trades" were performing their activities, and real-time measures were taken. Moreover, this room improved the quality of the works because different problems during the implementation were exposed and eliminated. The foreman teams discussed with one another one week before the construction in a specific Takt area improved their coordination and collaborated to overcome the common challenges. The expertise of the foreman provided practical solutions for different problems and improved the flow of information and the quality of work.

The principle of systematic completion that KHiB developed introduced the so-called "Table Test." Besides the testing room, all the systems which would be integrated into the project would be theoretically tested. It is called the Table Test because respective meetings, with the participation of specialists, facility managers, and end-users, were held and discussed the features of the systems. These systems had an effect on the Takt Plan, as a change in a system reflects the duration of its implementation.

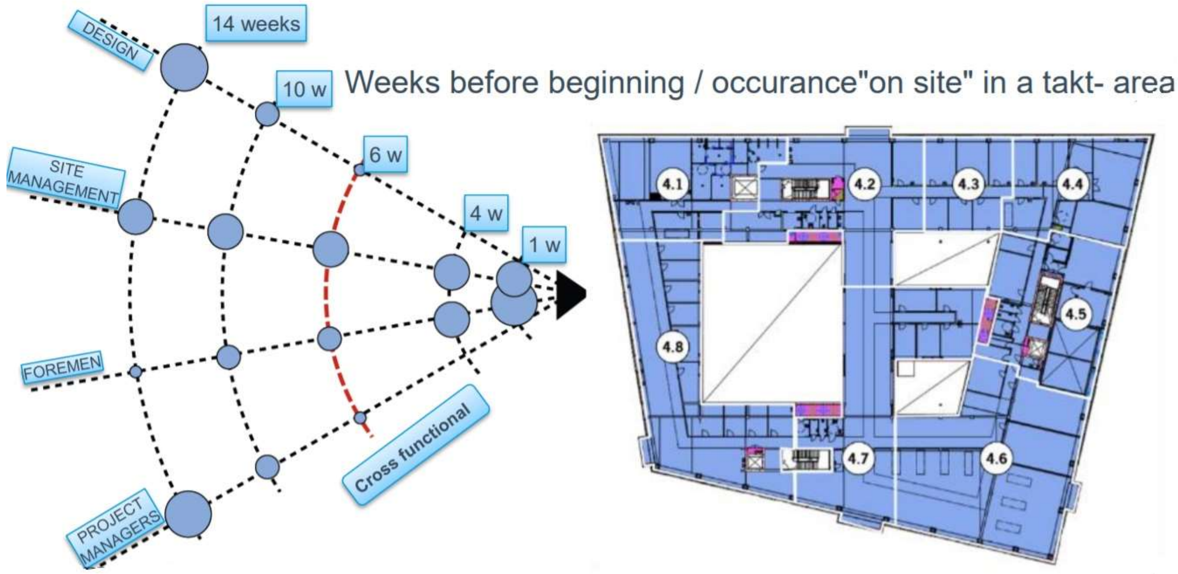


Figure 32: 14-10-6-4-1 preparation meetings. (Wertebach et al., 2017)

The project team considers the Takt schedule, not a usual way for planning construction activities. However, they agree that the easiness to embrace, the systematic approach, and the structured organizational movement of the trades that TTP provides improves the quality of construction and increases collaboration, which is the key to successful scope delivery. The steps that the project team followed to structure the activities with the TTP technique is provided below.

1. **Defining the control area.** The control areas on the KHiB project were around 400 m^2 and is indicated in the plan illustrated in figure 32 with numbers 4.1, 4.2, etc. These numbers indicate the floor where the control area is and the assigned number for each area, which disciplines the movement of the working trades on the same floor. A control area is the analogy of the Takt area that Frandson and Tommelein (2014) describe. The project team planned only one team per week would be in one control area. However, more detailed planning and trades performing specific systems in a location where the actual trade finished the job were allowed to be in the same control area. During the project, overlapping was minimized, and it was allowed only in the cases of underperformance for any activity that could compromise the Takt Plan. The activities happening in any control area are highly detailed.
2. **Parade of Trades** is differently called the train of activities, or the steps of the production process. The sequence for all the activities happening in any control area is outlined in detail. In the KHiB project, a train of activities is prepared for

the interior works, landscape works, the hall of the building (considered a separate zone due to the unique character regarding the design), and areas designated for technical support of the building. For each individual control area, the parade of trades is prepared separately. The sub-processes in between one activity of the train are detailed, so all the trades know the exact process they should do to achieve the desired result in terms of time and quality.

3. **Defining the Wagon.** A wagon is one activity of the train. For each wagon, there is a responsible trade. Theoretically, this means that one trade is assigned for one wagon. However, for practical reason, there was more than one trade assigned for an individual wagon in some cases. The project team assigned more than one trade in the cases when: (1) the completion time for consecutive activities is faster than the average completion time of other activities. In this case, the team grouped the activities and assigned the responsible trade, which would coordinate in between the same wagon; (2) when a certain activity is co-related with another smaller process, they are both under the responsibility of the same working trade.
4. **Defining Takt.** At this time, the Takt for each wagon of the parade of trades was one week. However, based on the size of the control areas, the Takt differs. This means that the quantity of work that has to be performed depends on the flexibility of Takt for each wagon. The load for each control area was calculated and tested (test room) before the construction started to work. Depending on the workload, the number of crews performing on different weeks in different locations was quantified beforehand to ensure a steady production process and reach the Takt milestones. This process is very critical, and the collaborative meetings with the contractors were vital. The contractors committed to designing their teams flexibly depending on the workload, and the authors emphasize the importance of awarding the contract to the contractors who rely on Lean principles and design the supply chain accordingly.
5. **Takt Plan** is drafted when a balance of the components described above was found. There is no information regarding the software used to illustrate the TTP. However, there is described precisely the location, the activities, time, and crews performing the activity. A descriptive map illustrating the location on certain floors, and the detailed processes for each wagon with the information over the trades performing it, was attached to the TTP as described in figure 33.

A critical part of a tight schedule like TTP is the monitoring phase. The participants should ensure that the progress rate on-site would be aligned with the planned production rate. To maintain the steady workflow and deliver the project in the desired quality, the project team considered every activity from several perspectives. There were several conditions which should have been fulfilled for every trade before moving to a new control area. This principle derives from TPS, where the whole production system was suspended if an integral part of the system was not delivering the required quality or there occurred any faulty process.

The first condition was to assure that there was no need for repair, and the quality was on the required levels. This was done in two ways: (1) the site management check and approves the delivery of the certain activity; (2) the successive trade would check every Friday (the last day of Takt) the readiness of the control area where they would start working. In both cases, the responsible trade was required to fulfill the required conditions. This created a chain effect in the collaboration between the trades. The quality was on the required levels, while the control areas were always ready for the successive works.

Other conditions that could affect the Takt plan included the information over the construction and processes, materials and other resources, knowledge of the workers, and qualitative working equipment. While the information flow was achiever mainly from the BIM model and BIM kiosks, which generated high transparency on all the processes, the other conditions were fulfilled from the fruity collaborative meetings and training with all the contractors. The necessary changes in the plan were done before the construction works took place, and all the participants were aware of the importance of the works they were performing.

Figure 33: TTP of KHiB project. (Statsbygg, 2017a)

Last but not least, conditions were the safety and preparation for the weather conditions. For the first one, a Safe job analysis was implemented in the construction site, while for the second one, under certain weather conditions, permissions from the site management were required to proceed.

During the implementation phase, regular meetings were held. Brief meetings of 15 minutes were held daily to discuss the current tasks and record any deviation from the plan. These meetings were named the "Taktboard meetings." Other than the progress against the plan, the focus of these meetings was also on the quality, safety issues, and tidiness of the Takt areas. The same procedures were done for each control area, and the participation of the responsible trade, the suppliers, site management, and contractors' supervisor was compulsory. The handover of each "wagon" to the other was part of these meetings.

6.1.5 Analysis of the case study

This case study presents a systematic approach to implementing TTP in construction projects. The roles of the participants are highly emphasized, and the tools to support the production flow are illustrated.

The structured participation of all the actors of this project starts since the procurement phase, when the project team decides to rely on contractors that implement Lean methodology into their activities. This facilitates the fast planning process as the subcontractors are aware and willing to commit to the project. However, their importance towards the project and the decision making is constant as all the contractors are an integral part of the production system.

The link between the design phase and the construction phase is done through a BIM model, which is delivered with the explicit goal of assisting the project development through all the stages. The role of BIM in this project is to increase the accuracy and visually illustrate the processes of the production to all the participants. During the implementation, the so-called BIM kiosks were directing the TTP into an agile perspective, as all the foreman were trained to deal with the new features that this project was providing.

For accurate planning, the project was divided into two main stages. The first stage consists of 14-10 weeks before the implementation. In this stage, the project team checked if all the drawings were correct, if they were able to deliver all the materials on time on site, and if they had all the subcontractors "on-board." The second stage was 6-4-1 weeks before the construction, which consisted of due diligence to the BIM model and verification if all the necessary information was included.

The 14-10-6-4-1 weeks before the production starts consists of regular meetings between all the participants and actors of the project. The division into two stages is done to highlight the engagement scale of each participant in different phases of the pre-construction phase. It also expresses the complexity of TTP implementation in construction when the number of stakeholders increases. On the other hand, the role that these stakeholders have towards the schedule defines whether a production system will be successful.

To ensure that the project would be delivered on the required quality, the project team followed the systematic completion approach: Plan it – Do it – Check it. This was enabled by providing the test room to the site. All the trades would perform their activities in this real size room. The results were studied into two perspectives: (1) if the planned Takt is the correct; (2) the quality of the works delivered was the right one. While the project team assessed the first one, the second one was controlled by the architect. However, the foreman started to perform their test activities only one week before the construction, and the project team highly suggests an earlier involvement.

The involvement of all the contractors in the planning phase also improved the design of different systems. By verifying the respective production systems beforehand, the project team changed the light systems as its implementation would extend the Takt plan by 25 weeks. The integration of the facility management department into the early stages to be able to virtually run the building had an effect on the Takt schedule. The contractors were asked to adjust the systems, which would create chaos on the schedule if it would be done during the production, and no BIM model would be available.

6.2 Residential building in Finland

This case study was conducted by Joonas Lehtovaara, Iina Mustonen, Petteri Peuronen, Olli Seppänen, and Anti Peltokorpi, published at the 27th Annual Conference of the International Group for Lean Construction (IGLC) in 2019, in Dublin, Ireland. The authors investigated the implementation of Takt Planning and Takt Control (TPTC) in residential projects. TPTC is a TTP schedule done during the construction, and it has gone through a lot of criticism due to time constraints in increasing its flexibility (Binninger, Dlouhy, Steuer, Haghsheno, 2017). However, for the purpose of this thesis, the analysis of this case study will focus more on the controlling phase of the TTP or the so-called Takt Control. Though a short description will be done to draw comparisons with the first case study, focusing more on the implementation phase will orient this research to find the complementary perspectives of different case studies.

6.2.1 Introduction

The integration of TPTC in this construction project consists of planning and monitoring the interior works distributed on seven floors. The total number of apartments is 42, and floors are not identical, thus compromising the desired repetitiveness and the sizes of Takt areas. The dimensions of apartments vary from 31 m^2 (single apartments) to 83 m^2 (three-rooms). However, the repetitiveness of the typology of the space eased the process of defining the Takt areas, shifting the planning issue to time definition. The contractual agreement was a design-build type. The general contractor (GC) was "Fira Oy," that was liable for the planning and implementation of TTP and contract awarding to the subcontractors.

6.2.2 Takt strategy

The main goal of implementing TTP in this project was to shorten the duration of the construction works without affecting the scope of the project. The first draft of TTP is achieved according to the steps that Adam Frandson and Iris Tommelein (2014) suggest, which are also described in this Master thesis on other chapters. Regarding the duration of all the tasks, Fira Oy relied on their own experience and their previous production rate database. Presenting the time terms to all the subcontractors was challenging because, for this project, the planning phase was overlapping with the contract awarding phase, so the GC did not have all the subcontractors on-board. However, the final draft of the TTP was prepared collaboratively (Lehtovaara et al., 2019).

The Takt areas corresponded with the number of apartments, and the size accordingly. Each apartment was divided into (1) dry works of the apartments; (2) toilets. This way, the two trains of activities could overlap with one another as they consist of different locations of the same Takt area, widely known as “standard space units” (SSU). Conditioned by the bottleneck activities, the faster activities were assigned to work on different locations on the same day, while the slowest ones had a higher Takt. The average Takt was one day for the apartments, while the common and storage areas were defined as different Takt areas, and they were considered separately (Lehtovaara et al., 2019).

For each SSU, the production process is considered in three stages: (1) Early Stage, which includes all the construction activities until painting of the areas; (2) Middle Stage, deals with the installation of floor finishes and installation of the equipment and devices on the ceiling; (3) End Stage, consists of the installation of doors, electrical fixtures, cleaning, and inspection before handover. The total duration of the interior works was eighteen weeks, and each of the stages consisted of six weeks, including the waiting times between the activities.

A characteristic of TPTC is that certain activities for different Takt areas can be combined into a larger area to accelerate the time terms, or vice versa, which results in lengthening the duration (Binninger, Dlouhy, Steuer, Haghsheno, 2017). However, the second option on this project was not an option as the team aimed to shorten the construction duration. Therefore, a combination of spaces for the handover space was planned, which consists of the end-stage of the schedule (Lehtovaara et al., 2019).

The schedule, as illustrated in figure 34, consists of some major waiting times due to the drying time constraints.

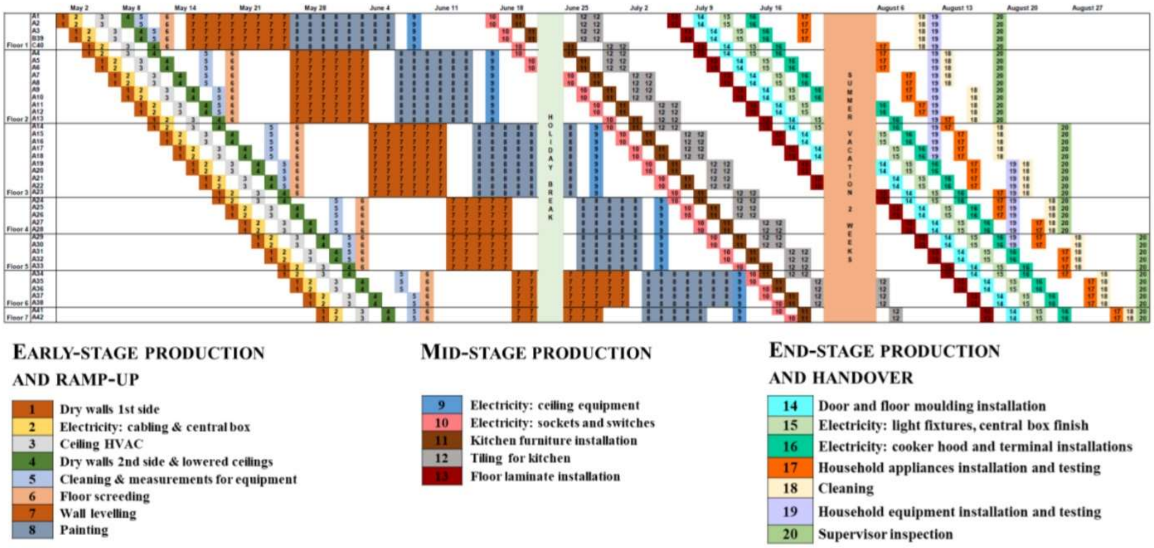


Figure 34: TTP for interior works of apartments. (Lehtovaara et al., 2019)

The optimization of the schedule on the dry spaces was done more straightforward than one of the toilets. Balancing the pace of the activities in these areas through resource optimization is conditioned by the size of the SSU. Therefore some activities located on toiled could not be aligned with one another. Moreover, “floor screeding” requires both of the SSU of the same Takt area. This means that the waiting time before starting the successive activities in the toilets required twenty days.

6.2.3 Takt control

During the implementation phase, the problems inherited from the procurement procedures came along. As mentioned above, the planning phase and procurement were overlapping. Therefore, the lack of necessary commitment of all the subcontractors regarding TTP led to unavoidable delays. Moreover, there was not enough time planned for the quality control of the works in the Takt areas. This means that while the trades were moving from one zone to another, there was not enough time to correct the defects and take measures to avoid repeating it.

Though there were planned three weekly meetings to track the progress and resolve all kinds of issues that could appear, the workers seemed not committed to increasing their productivity. This issue emerged from the payment method as they were paid on an hourly basis. Thus there was a lack of motivation to improve the performing pace combined with a lack of enough preparation to integrate TTP in this project, which led to a chaotic first week of construction.

These issues required taking corrective actions from site management. An analysis that the authors and the project board conducted lists the planning strategies that should have been made since the early planning stage to avoid the chaos of the first weeks: (1) integrate the logistics better to enable the Just-in-time concept of TPS; (2) orient the plan to give priorities to the critical activities that might affect a cascade delays such as partition walls, screed, etc.; (3) provide drying options and control effectively (in this project this was done through an inspection tool which generated real-time data for the inner air conditions); (4) the design of all the components of the building should be finished before the construction starts to the workflow will be not affected by any kind or nature of change that might arise.

The restart of the construction work after the corrective measures brought fresh energies to the site. However, new challenges regarding the activities happening in different SSU's of the same Takt area evolved. This problem is mainly related to the long drying time of the screed. The materials were on-site, but due to the nature of the works which require additional operating space, working for tiling the toilet and installing the laminate floor could not be carried at the same time in the same apartment. This problem, however, was balanced by the flexibility that other activities provide, such as electrical and mechanical installations. Moreover, the maturity of the management regarding the TTP approach (due to the nature of continuous improvement the TTP offers) increased the reaction time to correct mistakes and avoid delays.

On the other hand, the implementation of a digital tool from the project management enabled all the participants to retrieve the information from the history of the corrective actions taken, which improved the efficiency and self-performance of each trade. This led to an easement of the control on the last stage of the project. Although the project had several delays, the GC reported a total of 30 % time reduction while implementing TTP and a slight increase in the construction costs against the initial estimation (Lehtovaara et al., 2019).

6.2.4 Analysis of the case study

This case study introduces another level of complexity for TTP regarding the schedule itself regarding the overlap of the train of activities in different SSUs of the same Takt area. There is a lack of alignment between the size of SSUs and the nature of activities overlapping with one another. Moreover, the size of the SSU for the toilets highly impacts the alignment of the crews to balance the pace of the activities. The overlap of the toilet floor tiling and installing the laminate installation requires a micro-management and high coordination. However, if there is no collaboration between the trades, even the macro-management raises many question marks whether the quality of the works will be on the required levels.

In the case study, the buffers are not described for each planned activity, nor the risk mitigation measures such as waiting time between the trains to enable the corrective actions regarding quality and time for different activities before the train continues to move to the other Takt area. In this perspective, the redo work would have been avoided and would have also increased the awareness of the working trades for the required quality.

Moreover, the lack of timely preparation for this kind of schedule led to chaotic management in the first weeks, which, combined with TTP's tight nature, might result in high financial risks and quality compromise. The construction started when the building's mechanical project was not fully drafted, and clashes between the pipes and the structure of the building appeared, causing a small delay. For a successful implementation of TTP, the preparations should be linked since the design stage. Therefore, delivering a detailed BIM model that illustrates all the clashes between different systems applied to the building is necessary to create the right base for TTP. This, on the other hand, would also enable the possibility for a virtual meeting of the subcontractors with the deliverables before the project started.

On the other hand, the subcontractors and the supply chain could have been selected carefully based on the approach they have to the Lean Methodologies. This means that the condition on a contract award should not only be based on the bid targets but also on the vision and prior experiences. Another fact that should be highlighted is the procurement time. The Takt schedule should be done based on the selected subcontractors, and collaborative decisions and joint training to create the right working environment could have been made.

Having a Takt of one day emphasizes the importance of preparations beforehand. Having to deal with tight time terms incremented the stress of the workers on-site, which resulted in quality loss and stoppage for certain activities of the early stage. A reasonable decision would also be the involvement of the laborers in the planning and implementation of the Last Planner System, as Frandson et al. (2014) propose. As the authors describe, during the first weeks, there is a lot of misunderstandings between the subcontractors. This happened because they were not fully committed to the TTP, and there was a lack of information and communication between them. Developing a mutual understating and focusing on the mutual challenge to deliver the project on time and quality could minimize such problems during the production.

As described by the authors, the project was characterized by some wagon switches of the same sequence. These switches consisted of mechanical and electrical activities. The rotation of these kinds of activities enables a flexible aspect of TTP and allows the site management to take corrective measures and “assign” some “temporary buffers” for certain activities. This means that some activities can take a longer time to complete. However, this time should be recovered in the succeeding areas. On the other hand, the flexibility and willingness to change the sequence location from certain subcontractors express their commitment to the Takt schedule and their engagement in the overall process. The engagement and broad participation contribution of all the actors of the project, according to Frandson et al. (2014), is the key to a successful implementation of the Takt schedule.

The supply chain should be part of the plan as well, and there should be the right incentives to increase the motivation and involvement of the supply chain in the Takt plan. Associated with planning the right logistics, the storage of the materials should have been carefully designed for each wagon of the train. An example of the supply chain's importance is the lack of space for proper storage of the laminate and tiling. To improve the drying conditions of the screed, the management team decided to move the materials from one place to another, incrementing the damage risks and also creating unnecessary chaos on site.

The management team implemented a different digital tool to assess the air quality (Congrid), improve the collaboration, increase the awareness of the importance of the plan, and track the progress against the schedule *(SiteDrive)*. Overall, this decision resulted successfully, but the trades needed some time to embrace the new tools. The real-time data for the so-called critical activities generated valuable information for organizing the activities and rearranging the trades to avoid the plan's weekly slippage. However, there was not enough training for effective learning for the trades, and there was not an awareness of the potential that these tools had.

6.3 Anderson Lucchetti Women's and Children's Center (WCC)

This case study is published at "21st Annual Conference of the International of the International Group for Lean Construction (IGLC 21)" in 2013, and it is divided into two different papers: (1) "Takt Time Planning for Construction of Exterior Cladding," conducted by Adam Frandson, Klas Berghede, and Iris Tommelein; (2) "An Experiment in Takt Time Planning applied for Non-Repetitive Work," conducted by Meeli Linnik, Klas Berghede, and Glenn Ballard.

6.3.1 Introduction

The WCC is an eight-story building located in Sacramento, California, and it is part of the health care campus program, which consists of the renovation of existing structures and building new medical facilities (Boldt, 2012). The 36820 m^2 (395 241 ft^2) of this project include 214 beds, neurosurgery rooms, a birthing center, pediatric care, and different typologies of high-risk surgery spaces.

The need to implement TTP to decrease the implementation duration of the project derives from the high demand that the zone has for hospital facilities (Eesti Timmitud Ehituse Tugirühm, 2016). As Linnik (2016) agrees in the presentation at "Eesti Timmitud Ehituse Tugirühm" over TTP implementation in hospital projects, the zone has a seismic character, and the existing facilities are not all earthquake-proof. Therefore, the need to have functional hospitals in case of any natural disaster, new methodologies have been experimented in order to accelerate the implementation time.

The general contractor or the project was The Boldt Company, which followed an Integrated Lean Project Delivery methodology (a methodology that merges Lean principles into contract structures to prevent cost overruns, improve quality, and increase participant's collaboration (Lean IPD, n.d)). To achieve this, besides the Lean construction principles, a BIM model of the project was delivered, which was used since the early stages of the project to increase the accuracy and provide all the necessary information for proper planning and cost estimation. Moreover, a cost-plus type of contract *("Integrated Form of Agreement IFOA")* was used between the GC and the subcontractors (Boldt, 2012).

6.3.2 Takt strategy

The production process system design is based on the demand for these kinds of buildings, which derives from the need for hospitals (Linnik, 2016). However, quantifying the demand accurately in terms of time required a long process and a wide collaboration of all the participants. According to the author, planning is the reason for poor performance in construction. Therefore, in this project, the Last Planner System and Takt Time Planning was integrated.

The planning phase of this project is done collaboratively, with the participation of all the working trades. Their professional knowledge is the foundation for the planning phase (Linnik, 2016). The author, during the presentation, agrees that the idea of having one responsible PM, which provides a detailed plan and enforces the production system based on this plan, is not the case in this project. For this project, the project team pulled the information, regarding the duration for each activity, from the working trades to produce an initial plan. This plan, which included the assumed number of labor for each working trade to achieve the suggested time target, was later analyzed and aligned to build a continuous flow on the site.

Integrating Takt in this project began as an experiment for the exterior works. (Frandson et al., 2013) explain that it was followed by an interior framework of TTP implementation. According to the authors, after identifying the activities that occur for the installation of cladding, the sequence is defined, and the Takt zone accordingly. TTP was parallelized with a traffic flow, where the pace of activities represent different speeds that the trades have on site. In contrast with the traffic flow, the intention that the project team had was to identify the slowest activities that might induce time waste and disrupt the construction flow (Linnik, 2016).

For the duration of each sequence of the trade, as explained above, the experience of each working trade was valuable in defining the final schedule. The project team concluded in four Takt zones, and the sequence as follows: (1) framing; (2) window installation; (3) scaffolding; (4) sheeting; (5) first waterproofing; (6) second waterproofing; (7) patching.

The Takt was established four days, and the framing was recognized as the bottleneck activity. For this reason, the framing crews was doubled. The GC was responsible for monitoring the progress. During the implementation, all the trades had a supervisor, which, according to the management structure of the project, was named “superintendent.” The superintendent of each team collaborates with the superintendent of other teams, and also the general superintendent and the site management. All the final decisions would be approved by the general superintendent. The coordination and the information level was high, as the management structure was designed that way, and everything was updated in real-time (Frandson et al., 2013).

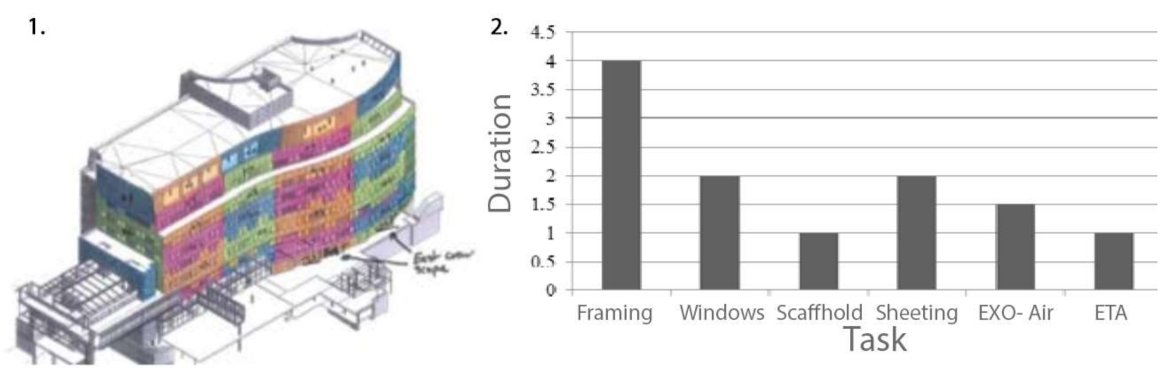


Figure 35: Takt zones and Takt time. 1. The BIM model is used to illustrate the zones and working trades. 2. Definition of Takt for the processes of one sequence. (Frandson et al., 2013)

As the working trades individually took responsibility in the early stage, the commitment towards the final schedule was wide. The integrated contractual management, which consisted of the distribution of all the project cost surplus into all the contractors, motivated the participants not only to perform the project collaboratively but also to reduce the individual buffer and corresponding costs. This means that contractors were inclined to think for the project as a whole, not to take only the fixed contractual profit, but also the collective reward (Linnik, 2016).

The BIM model was used to provide the high accuracy of the information and was also integrated into the supply chain. Daily material deliveries were done based on the combination of the daily quantity needed to perform the work and the site storage capacities. As Frandson et al. (2013) explain, if the progress is made based on daily production, then the support to the site is to be done on different levels and on different perspectives. This means that the importance of performing the daily production plan weighs the same as all the other components linked to it, as the whole work depends on every perspective of a single activity.

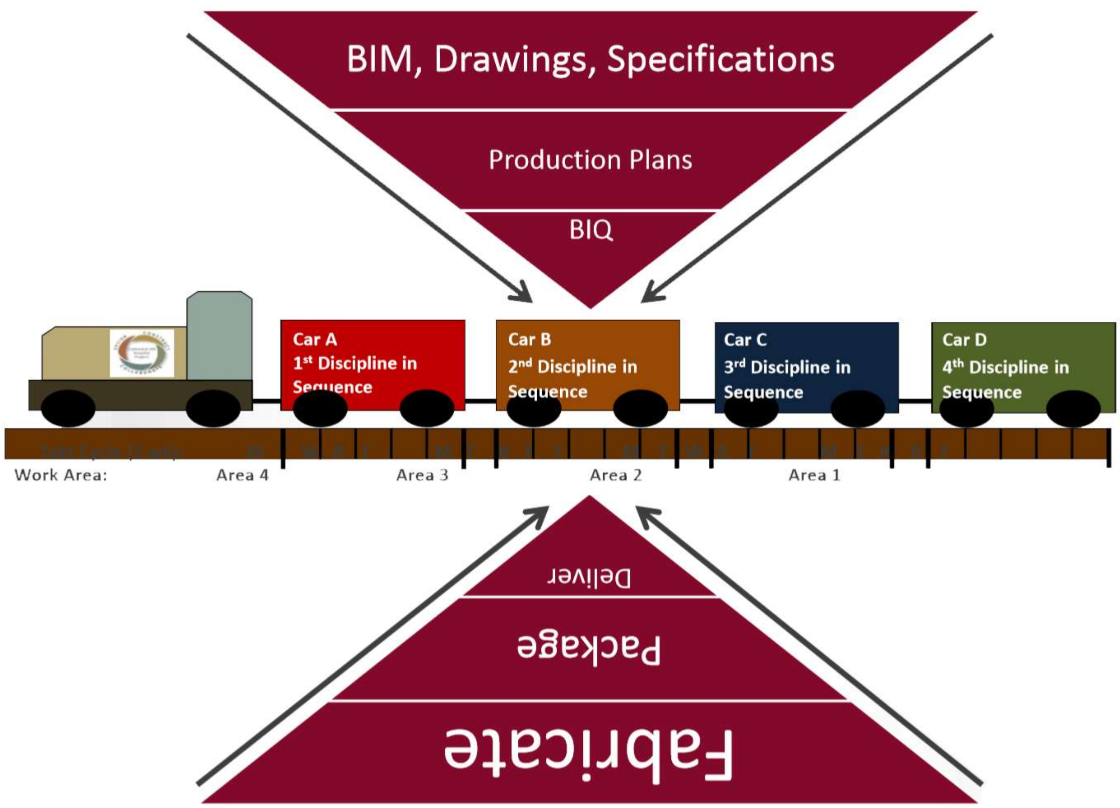


Figure 36: Level of detail in TTP. (Linnik, 2016)

The implementation of TTP in interior works was the second stage of this experiment. Implementing the Takt in interior works was done through the steps that Frandson et al. (2014) describe, which are described in the other chapters of this thesis. As Linnik et al. (2013) outline, the sequence and the duration for each trade were done through “pull” collaborative meetings of the LPS.

Takt's challenge in this project was mainly to define the balance of the resources, time, and information as the determined Takt areas had a low level of repetitiveness. Therefore, in cases where Takt could not be met, according to Linnik et al. (2013), the area structure was adjusted but not segregated, and the operation's design was modified. This means that the focus was more on bottleneck activities, to improve their pace continuously, and to achieve the flexibility to reach the five-day Takt planned by the project team.

In this case study, for certain activities, the TTP detailing level goes into hourly schedules. This, according to the authors, led to the optimization of operations between the trades as they were committed to the schedule. The authors refer to the door contractor that developed a preparation station to express the changes into processes that participants made to reach their productivity levels. However, there are contradicts in the opinions regarding the overall production rate improvement as the non-bottleneck activities did not significantly change their operational productivity.

On the other hand, each trade supervisor was responsible for making sure that at the end of each Takt in a certain zone, the works were delivered in the required quality, and the Takt area was ready for the next trade moving in. This required detailed coordination, especially in the cases when the quality was not reached. The project team supported the working trades in terms of resources into the self-improvement process, so the defects or lack of quality would not be repeated in other areas. The motivation to avoid redo works was also prone to the contractual typology, as explained above. As Linnik (2016) explains, the contractors were open to spend more capital on improving the process and quality, as they knew that the extra expenditures would be returned.

Also, in order to improve the collaboration between the trades and minimize the risk of failures, lookahead meetings were held for a duration varying from five to ten days, depending on the nature of activities (Linnik et al., 2013). These lookahead meetings were also held with the supply chain participants to be fully aligned with the corresponding planned production flow.

The work for the exterior cladding was initially on the master schedule planned for eleven months, and it was delivered in five months when Takt was implemented (Frandson et al., 2013). Moreover, though the bottleneck's activities (framing) had double resources to optimize and balance the Takt, the net savings were estimated at $12 million (Linnik et al., 2013). However, as the authors conclude, the cost-saving estimation was not rigorous during all the construction duration, as the teams could not capture the savings accurately at the beginning of the implementation phase.

6.3.3 Analysis of the case study

The WCC case study introduces a successful experiment of TTP implementation on the exterior works of a project and non-repetitive interior works. The structure of integrating TTP as a work structure model in this project provides a reliable approach to the components that should be taken into consideration when fast pace construction is required.

The decision for the model of used contractual agreement strengthens the team and increases the level of participation. Contractors are motivated to improve the quality of their deliverables while minimizing the costs and overall duration. However, this delicate decision requires another level of mindset in the project, and at the same time, structured and diligent supervision. While benefits might be the motivation for each subcontractor to take risks, the quality of work and the project's scope should remain the priority of all the operations.

In this case study, during the implementation of exterior works, different tasks were required to be delivered, which were not originally planned. This compromises the pace of works and the contractual agreements and might result in claims from the project participants. However, the contractors' proactive nature assured high flexibility to the project by delivering it on time while including the extra works. This illustrates the importance of the contractors on the project success and the mindset that Lean Construction in general and TTP in particular require.

The importance of collaboration is also emphasized by the participation of the foreman in the planning phase. This means that the practical experience combined with theoretical principles defines a TTP plan correctly. The LPS provides broad participation in the project decision making and individual responsibilities, and its integration in a Takt plan increases the reliability of the schedule. The meetings organized by the project team enable a wide-scale information flow. All the units of the parade of trades know the importance of delivering their work into the required standards for the successive wagon. At the same time, all the participants are aware of the significance that remaining to the plan has. This, in many cases, avoids micromanagement, which in high scale projects might be challenging to achieve.

The BIM usage to support TTP implementation is essential considering the amount of information and the level of detail that each sequence requires. Also, the accuracy level in terms of quantities is vital in avoiding the waste principle of Lean and implementing the JiT principle on site. On the other hand, dividing the workload into comparable amounts is achieved better if BIM is used since the early stages of the project. In addition, handling accurate information allows contractors and all the participants to facilitate and improve their production processes. Eventually, the delivery time decreases, and the efficiency of resource usage is improved.

Meeli Linnik (2016), during the presentation of Lean methodology with the focus on LPS and TTP in Thalin, Estonia, illustrates the importance of BIM with the groundwork works phase of the project. The subcontractor insisted on not removing all the soil from the site as they planned to reuse it again in the backfilling phase, and it would increase the project costs if they would remove it and bring it back in the later stage. However, the amount of soil needed for this phase was much less than the subcontractor planned. The project team used BIM to calculate the precise amount of soil required, which resulted in a win-win situation for both parties. This way, the site management could better manage the site by managing better the on-site inventories. The subcontractor had an exact estimation of the amount of soil needed for backfilling. The accuracy of information combined with the location break down structure (BIM) improves the Takt schedule components, as Melzner (2019) suggests.

The approach of proactivity also applies to the supply chain, as Linnik (2016) indicates. In the WCC project, every subcontractor was responsible for organizing the corresponding supply chain, which was done successfully. However, the site manager had to coordinate in order to manage the on-site inventory better and not interfering with the movement of the trades into different Takt areas. Organizing the operations on this case study demonstrates the significance that the managerial project structure has in facilitating the TTP and supporting the trades performing their works and, at the same time, the organizational aspects of a Takt schedule.

This case study also illustrates the drawbacks that bottleneck activities have toward faster operations. Hence, as the authors state, there can be losses in the capacity as the more rapid activities are required to align to the slower Takt. For this reason, collaboration and the production process transparency are vital in maintaining the same progress rate and, at the same time, work efficiently to avoid time wastes. The process for the bottleneck activities was highly detailed, which in this case study, resulted in an optimized flow. However, the accurate cost aspect could not be adequately captured.

7. The implementation guideline of Takt Time Planning in construction projects

Adding value to the projects is the main principle of Lean philosophy. Many projects, including the ones analyzed in the case studies of this thesis, illustrate the continuous flow that TTP aims to generate. The combination of the regular time interval and the needed transparency, in terms of information flow that such a tight plan requires, build the foundation for the continuous improvement, on which the productivity efficiency of TTP relies.

Because of the condensed nature of this plan, the information flow during the implementation is quite challenging. Considering that construction projects are subject to continuous changes, the preparations of TTP should begin in the early stages of the project. Referring to the first case study of this thesis, the integration of Takt in the project was presented since the design stage. However, this does not mean that the design should limit to the Takt optimization. Instead, it consists of three main keynotes, (1) the used materials, (2) the way of building, (3) the BIM model. These three concepts are divided and linked at the same time at one another.

Avoiding huge on-site inventories facilitates the process of movements of the trades and avoids potential damages of the materials. Scheduling the project using TTP and realizing that materials cannot be easily found and delivered on time compromises the whole schedule, and will generate time waste on the implementation phase. Therefore, using materials that can be quickly provided on a timely basis not only improves the TTP implementation but also aligns a Takted supply chain to the schedule. The same applies to the building methodology. In this thesis, it is not conducted an off-site Takt as it is similar to the manufacturing Just-in-Time principle. However, the cost assessment should be calculated before deciding to build an off-site production system.

The BIM model, on the other hand, links the optimization of the design and the quality of TTP implementation. In this case a BIM manager is required. The phase definition of the BIM model determines accurately the sequences of the work, and the work chunks. The workload can be divided comparatively equal so that the Takt can be defined universally for all the areas and the linked crews. Moreover, a BIM model is the first introduction to all the project participants and their responsibilities; it is the foundation of constructive and collaborative decision-making. The participants can virtually meet the project requirements. The level of detail in the BIM model has a direct impact on the quality of TTP integration eventually, and it is an added value by extending the schedule's flexibility boundaries and transmitting accurate information to all the project participants.

The outcome from the design stage should include all the necessary information for the project development, including a master schedule and the first draft of the TTP. The timeframe of this draft defines the contractual durations.

As presented in the case studies, the procurement phase is the stage where the project "meets" all the participants. The contractual agreements with the contractors will be based on the milestones of the master schedule. These milestones define the production demand, and reverse scheduling is done to draw the Takt schedule. The involvement of the participants at this phase focuses on four key issues: (1) contract reliable contractors; (2) motivation of the contractors to commit to TTP; (3) assess the supply chain; (4) technical support from the project team.

As analyzed in the first case study, the biggest problem of Lean implementation in general and TTP specifically is the path-dependent idea: "we have done it always this way". Therefore, finding visionary contractors with the right attitude defines the success of such a schedule. Selecting the contractors who rely their activity on Lean principles must be specified in the tendering description.

The participants tend to finish the work they are responsible for and not get involved in the overall process, which should not be the case in projects that integrate TTP. Hence, different forms of motivating the contractors to improve the schedule and the project quality that should be used. One way can be the "Integrated Form of Agreement," which is explained in the third case study. Dividing the cost surplus at the end of the project not only motivates the contractors to commit to the plan but also increases their investment toward the quality, in order to avoid the redo.

The TTP should not be a form of transferring the risk of the project team to the contractors and subcontractors. The project team should conduct training for the participants and ensure that the contractors and the supply chain are linked and committed to the plan. Therefore, collaborative meetings between the contractors, the respective supply chain, and the project team should be conducted before drafting the final Takt schedule. In these meetings, different systems applied to the project should be discussed and assessed virtually on the BIM model. The assessment is done not only to align the different perspectives of the schedule but also for the participants to provide on the table other options which might improve the quality, minimize the costs, or improve the schedule.

The final Takt plan should be decided collaboratively between all the participants. All the contractors should define the duration of their tasks, and at the same time, discuss with interdepended and subsequent crews for the handoffs and the quality of complementary tasks. For this purpose, the Last Planner System knowledge facilitates the process. The project team should possess a comprehensive understanding of LPS, and training on the contractor's participants is also required.

The TTP itself can be generated with the steps that Frandson (2019) presents: (1) Data collection; (2) Zone and Takt time definition; (3) Trade sequence identification; (4) Balancing the plan; (5) Finalization of the schedule; (6) Plan execution; (7) Update the plan regularly. However, different measures to mitigate the failure risk should be taken in this method. As analyzed in the second case study, a soft start is recommended to avoid the chaos on site. This means that different trains should not begin simultaneously so that the plan can be assessed and improved on time. Also, another measure that should be included in the plan is the train stoppage at the end of the first sequence, to assess to quality of the schedule and also the work quality that should be checked if it is at the required levels.

The train stoppage is a mechanism used in the Toyota Production System, where the focus was only on the quality, and in case of a defect, the production system was shut down. However, assessing the quality of the schedule and the tasks should not be done only during the implementation phase. As described in the first case study, for the systematic completion methodology "Plan it - Test it - Do it", the test room is the mechanism that optimizes better the TTP. Before each crew starts to work on-site, a real-size test room should be implemented. This will enhance the collaboration between the trades. The transparency of information will also include the required quality by the project team, and also what sequent trades expect from one another in terms of zone conditions and overlapping processes.

The BIM model produced since the early stages of the project definition should be adapted to TTP, and information should be accessible during all the time on site. The so-called BIM kiosks can be used depending on the scale of construction. VR can also be a tool that may enhance the relationship between the foreman and the work that needs to be done. During the implementation, as illustrated in the second case study, the different tools can be used to assess the drying times and completions. SiteDrive is one tool that is used widely in Finland to track the progress of the projects that use the TTP scheduling technique. In addition, lookahead meeting should be conducted regularly to maintain the consistency of the schedule and collaborative commitment to the plan and the quality.

During the implementation, the TTP is under continuous improvement as all the trades already master the work they perform. Therefore, the constant updating of the plan is required. The schedule should be updated based on the data collected on the regular meeting, Takt board, or by the data reported by the trades to respective supervisors. A timeline of the corrective actions should also be recorded, and the information should be accessible to all participants. Specific trades can improve themselves based on the nature of difficulties and the corresponding corrective action taken.

7.1 Proposed Framework and Recommendations

The proposed framework based on the literature review and the information that the case studies provide is illustrated in figure 37 and consists of five phases: (1) Design phase; (2) Planning phase; (3) Tendering phase; (4) Pre-construction phase; (5) Construction phase.

Succeeding with TTP requires accurate design specifications, and decisions that facilitate its implementation. The availability of the used materials is vital in planning a fast schedule as TTP. Increasing the accuracy of the work density and detailing at the right level, the project's information is also a crucial element in the production system design. Therefore, using a BIM model at the early stages of the project definition provides accurate information regarding the division of the workload and processes in different areas of TTP.

The first draft of TTP can be scheduled after defining the demand. The demand is the concept derived from the TPS and defined in construction by the milestones of the Master Schedule. Planning with LSMS illustrates the time wastes between the activities and gives an overall information regarding the activities that require more adjustments.

The milestones of the Master Schedule are performance indicators for the success of TTP in terms of duration, and at the same time, they set the minimum required production rate. The information on the first TTP sets the boundaries of the negotiation process with the contractors.

The selection of the contractors, on the other hand, is based on various criteria, so the process of TTP implementation will not face social obstacles. One of the criteria would be the invitation to bid to contractors that rely on their operations based on Lean philosophy. Moreover, the contractors must have the resource capacities and adequate supply chain in order to support the project implementation at different levels.

The final Takt schedule is done in collaboration with all the selected contractors. Setting a common target requires different kinds of training, which is provided by the management team. Training includes different planning involvement mechanisms and tools and also measures for the Takt control phase. Defining a successful plan also requires the involvement of the supply chain. It is recommended in this phase for the project team to have an LPS member with extended knowledge in order to facilitate the whole process.

The tight nature of the TTP requires different steps of the optimization. The practical knowledge of the “last planners” into defining the duration of their activities for different work densities can be tested in a real-size testing area. The crews can perform their wagons of the train in order to assess the reliability of the drafted plan realistically. On the other hand, due diligence in the testing period is required to assess the quality of works. The final optimization of the TTP is done after the testing step, and meetings with different contractors should be held to optimize the quality of the performed works.

During the execution phase, regular meetings should be held. These meetings include short daily meetings to check the progress and timely based lookahead meetings to optimize the plan further. It is recommended that all the foreman should report in the case the Takt is not reachable so that on-time corrective actions can be taken and cascading delays can be prevented.

Takt control includes a continuous optimization of the plan because all the working crews master their task as they perform it in different zones.

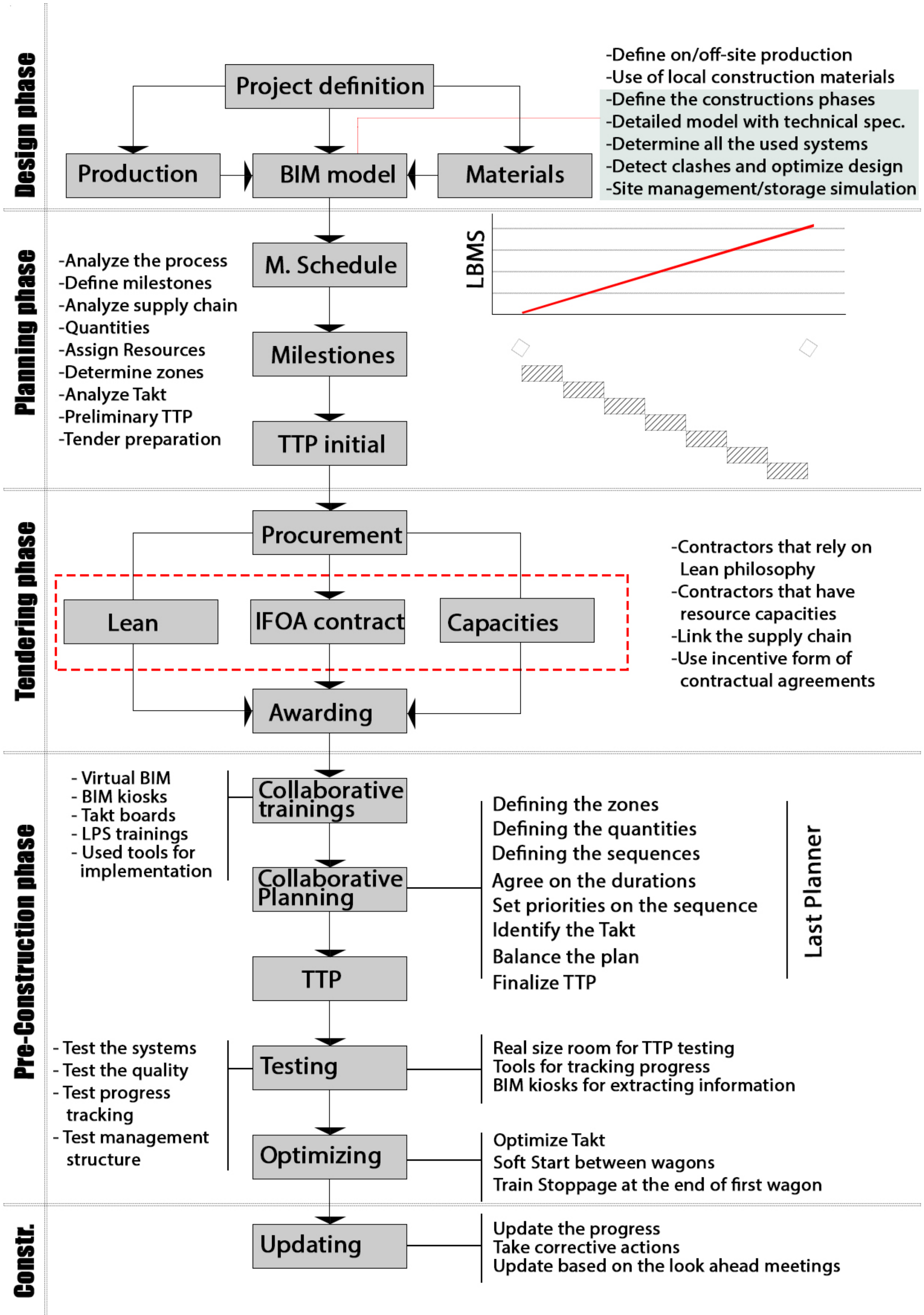


Figure 37: Conceptual framework for TTP implementation guideline in construction projects.

7.2 Discussions

To the author's knowledge, this is the first research that explores the implementation of Takt Time Planning in a construction project starting from the design phase. Several implementation facilitators were identified as succeeding with this scheduling technique. Part of these facilitators presented in this thesis was also conducted by Adam Frandson (2019) in his dissertation thesis, in the chapter pre-conditions of Takt Time Planning. However, Frandson refers to these pre-conditions as recommendations to present TTP as a work structuring method.

When proposing this thesis, the idea behind the TTP implementation guideline was to analyze different components of construction projects and present TTP as a structuring method to improve the efficiency of construction projects based on the profile of each tasks. However, as a Lean tool, the implementation of TTP requires a new working mentality, a new working mindset. Therefore, the author has conducted the research based on different phases of construction and combines TTP with other tools, which serve to add more value to the construction projects.

Value on the projects is the main principle of Lean philosophy. Many projects, including the ones analyzed in the case studies of this thesis, illustrate the continuous flow that TTP aims to generate. The combination of the regular time interval and the needed transparency in terms of information flow that such a tight plan requires build the foundation for the continuous improvement, on which the productivity efficiency thinking of TTP relies.

The case studies in this thesis illustrate that the overall duration of the implementation phase is shortened considerably. However, this does not indicate that TTP improves productivity. Instead, it enhances the efficiency of the construction sites by applying a systematic approach to the production systems and making the process visible, more transparent and manageable.

The focus of TTP is not to work faster but to enhance the coordination of the production system. Implementing TTP means including the right people, choosing the right time and the right zone, using the proper methods and means, and detailing the project at the right level. It is a matter of combination of different perspectives of the "right" approach. The discipline of the schedule requires broad collaboration and participation. At this point it is clear that every member is important, each actor counts. Through the clarification of the importance of each actor the cohesion and the sense of collaboration between the members should grow.

The collaboration between all the participants is the foundation of planning in a realistic approach and having a common goal: finishing the project on time, on the required quality, and within the budget. Different instruments and mechanisms can be used to optimize the whole TTP and reach the common objective. The guideline of TTP integration in construction projects can also be described in three main collaborative phases: (1) the preparatory phase; (2) designing the production system phase; (3) the testing and updating phase.

In the preparatory phase, the management team collaborates with all the specialists in the different fields to prepare all the necessary documentation and required specifications. In this phase, the foundation of TTP success is built. The main focus is on preparing a product, which can be managed and delivered efficiently. In this sense, the design should be optimized. Different tools such as BIM should be used, and also the right contractors should be selected. Finding contractual incentive forms is a critical aspect of the later success of the plan.

The second phase consists of the design of the production systems. In this phase, the collaboration of all the contractors and the management team is vital for scheduling a comprehensive plan. The key solution is to have a schedule that is built by the ones who are going to perform it. The duration of each work chunk, which is determined by the respective contractors, is collected and analyzed by the management team to determine the Takt and assign the adequate resources so that the reachability of the milestones is realistic.

In this phase, an essential part of the plan is also the logistics for Takt control. The supply chain is highly dependent on the set Takt as the availability for storing materials on-site is limited. Hence, material flow management is one of the most critical perspectives of the components of a Takt plan. The logistics also consists of the responsible structure for the quality control and progress assessment. Therefore, a realistic and reliable Takt duration should not only take into consideration the duration for each work chunk, the areas, and the assigned human resources. Collaborative meetings should be held with the suppliers, and an implementation strategy should be determined.

The last phase consists of the phase in which reliable assessments of the plan and corrective decisions are made. A testing simulation of TTP can be done in a real size testing area, where all the systems will be performed as the described processes of the plan. The cost of this test should be included in the overall cost estimations. Based on the gathered data, the schedule can be optimized, and quality expectations are transparent for all the trades.

A Takt plan is a plan that improves constantly as the trades repeat performing the same tasks, the supply chain is mapped to the production system, and corrective measures are consistent. Regular update based on the performance of the trades is required in order to optimize the production system accordingly. The combination of TTP and LPS in the described phases two and three adds value to the production system. It boosts the communication and collaboration between all the participants, which is the pillar of a successful Takt implementation.

Another key element in the Takt implementation is the required constant support by the management team to the Takt production. During the execution, different tools can be used to support the trades, such as Congid or SiteDrive, which assess the physical state of materials (if there is the need for the drying period) and track the progress and provide the necessary information in real-time. BIM can be used during all the stages of TTP implementation, including the so-called BIM kiosk that provides all the required specifications.

7.3 Research Questions Answers

How is TTP generated and implemented? How does it impact the Master Schedule?

This question is answered in subchapter 5.3 of this thesis. When Takt is intented to be used in a construction project, it can be generated mainly in six steps:

1. Collect data from the Master Schedule.
   The data includes the duration of the activities, quantities, location in case LBMS is used as a scheduling technique, interdependency relation between the activities, and the planned resources.
2. Identify the areas.

The area identification is made based on two main categories: (1) the nature of the activities happening in a certain area; (2) the quantities of works are comparable.

3. Recognize the trade order.

   Based on the selected areas, an analysis of the activities is done, and each activity is divided into processes and sub-processes, known as work chunks. The trade order is differently known as the train of activities, and the wagons of the train represent the work chunks.

4. Synchronize the workflow.

   For each work chunk, the duration is determined, and the synchronization is done based on the pace of bottleneck activities. The first step in the synchronization is improving as much as possible these activities, then the Takt is determined based on the average time of all the activities of the sequence. A detailed explanation for this step is presented in figure 19.

5. Assess all the trades' adjustments.

   In order to increase the reliability of the plan, all the adjustments to the pace of activities should be consulted with the correspondent professionals and executers. In this stage, all the contractors and the supply chain commit to the plan. Moreover, the final assessment of the plan is done to adjust to the Takt control phase. It is recommended a soft start for the trains, and a train stoppage plan at the completion time, to extend the flexibility borders of the TTP.

6. Takt Time Plan.

   A final TTP is generated, including all the adjusting mechanisms, Takt zones, trains, resources for each wagon, and the movement path of the train.

TTP is a fast schedule. Therefore, the milestones set in a Master Schedule are reached faster when TTP is used as a work structuring method. Depending on the percentage of the activities scheduled with the TTP method, the Master Schedule is subject to continuous updates based on the progress rate of TTP activities. When LBMS is used as a planning method for the Master Schedule, the TTP plan can be attached to the Master Schedule, and the flowlines are fully synchronized with one another. On the other hand, smoothing and leveling the resource graph in the Master Schedule is challenging as it compromises the discipline of TTP.

The impact of TTP on construction sites regarding time, quality, and cost. Pull and push strategy, the effects of Takt in the cash flow? Cost related results of Takt?

The answer to this question is covered in the literature review chapters and in the case studies of this thesis. It is universally recognized that TTP shortens the duration of implementation of construction projects. In the case studies it is estimated that the duration is improved from 30 to 50 %.

In construction, time and cost are closely related. The longer the duration of activities, the higher the overall costs. This connection is mainly derived from the resources' costs, overproduction, or underproduction. As explained in chapter five of this thesis, improving the pace of slower activities consists primarily of adding extra crews. The overall result of TTP implementation in construction is also an overall cost improvement. The extra resource costs are balanced from the activities which require fewer resources to reach the Takt. Moreover, as explained in the TPS section, TTP aims to eliminate overproduction. In the third case study, the project's costs were decreased by $2 million when TTP was used as a work structuring method for exterior cladding.

The case studies one and three present an improvement of the quality of works. Theoretically, TTP aims to avoid redo. This is a principle presented and derived from TPS, which predicts the stoppage of all works in case any activity is not delivered properly. However, the contractors should have the right contractual motivation in investing in order to reach the expected quality while maintaining the fast pace of performance. This is done through different incentive types of contracts such as IFOA, which is presented in the third case study. The contractors and the management share the risks and benefits. This is an important incentive in terms of reaching the required quality, avoid redo, and maintain the planned progress.

In addition, a different form of contract between the contractors and their crews are recommended. As illustrated in the second case study, the crews which are paid on an hourly basis have not the right motivation to finish their tasks faster. As mentioned chapter 7.1, TTP is a collaborative plan, and it relies on the participants. Different forms of involvement improve the triple constrains triangle of project management.

Though TTP, when LPS is used for reverse-phase planning, is considered a pull method, it remains a push methodology as it aims for fast implementation. In terms of cash flow, the time improvement overweight adjusting the plan for more balanced cash flow.

Buffer Management in TTP, comparative analysis.

The time and space buffer in on other scheduling techniques aims to mitigate the risk of constructions' activities implementation due to unforeseeable conditions. On a TTP schedule, these buffers are eliminated as they are considered a time waste. However, in TTP, there is another kind of buffer, which is known as a capacity buffer. A TTP consists of increasing the speed of slower activities and slowing down the faster ones to reach the Takt. The capacity buffer is the difference between the Takt time and the original execution time of more rapid activities. Theoretically, this kind of buffer is considered a time waste as the trade performs the activity fast and has to wait a particular time to move to another Takt area. Practically, this time is used to improve the plan and for the resources to involve in additional unplanned activities on site. Depending on the nature of the activities and the collaboration between the trades, the capacity buffer can also be used to optimize the slower tasks further.

On the other hand, a train of activities is in many cases by empty wagons. This does not indicate a time or a space buffer; instead, it indicates a waiting time for the tasks that require a drying period. In the specific area might develop activities which do not compromise the drying task. This happens in cases of corrective measures for certain activities, and in most cases requires an additional crew as the main one should work in another planned area.

Monitoring and Controlling in Takt projects, how to maintain and optimize the activities pace?

Takt control is the most critical phase of TTP. Considering the tight nature of such a plan, the corrective actions during the execution phase are limited to the adjusted Takt. Therefore, different adjusting mechanisms are set since the planning phase. As discussed in the guideline framework chapter, the assessment of TTP is key regarding successful implementation. Besides the testing room and collaborative meetings, there are recommended two main mechanisms that facilitate and enhance the flexibility borders of a TTP: (1) soft start between the trains; (2) the train stoppage with a Takt duration, at its completion time. The first one enables the corrections of the second train based on the experience of the first train. The second one allows revisions to in between the same train and also assesses the quality of the delivered works in order to set a common ground.

Two crucial aspects of the Takt control phase are information transparency and the managerial structure aspect. The amount of information is high for a short Takt period. Therefore, using the advanced methods and means to enable the data is necessary. The first case study introduced the concept of BIM kiosks, which allows all the crews to retrieve information not only regarding other tasks but also for interconnected tasks. The information also includes the records of corrective actions taken so that the crews can improve based on previous experience.

The organizational structure is crucial in terms of supervising and documenting. The so-called “shopfloor management” is responsible for organizing daily meetings to discuss and collect information for daily tasks and document all the information on time to accelerate the potential corrective actions. Based on daily discussions, the management team can decide for further support of specific crews to maintain the planned progress. The corrective actions’ period is dependent on the Takt, and daily due diligence is required to align the plan and the progress. Different tools are developed to track the progress in Takt projects, such as SiteDrive. On the other hand, the Takt control phase also consists of lookahead meetings, aiming to optimize the schedule based on actual progress and increase the participation levels in decision making.

As discussed in chapter seven, TTP is a collaborative plan. It is the responsibility of each individual to report if there will be deviations from the schedule and ask for further support. Daily supervising, in many cases, might be contradictory to the social aspect and further increases the pressure of performing crews. However, it is crucial in terms of the successful implementation of the plan. During the Takt control phase, the TTP is continuously under update as the crews perform and improve. It is also required preparatory training for all the working units before the construction begins.

Takt implementation guideline.

Takt Time Planning implementation guideline is presented in section 7.1 of this thesis.

8. Conclusions

Takt Time Planning is a phased schedule that is developed between the Master Schedule and Lookahead processes, which consists of balancing the duration of all the construction processes and it enhances the efficiency of sites by applying a systematic development approach to the production systems. The focus of TTP is to identify and analyze the construction processes deeply to determine a clear and balanced flow by adding continuous value to the construction projects.

The milestones of the Master Schedule set the demand for the production of TTP. On the other hand, these milestones are a KPI for the productivity improvements of the site. However, using the TTP scheduling technique does not make a slow team working faster, but it improves the coordination of the production system. The coordination is done by identifying clear working areas, avoid overlapping by planning a disciplined movement of the working crews in different locations and different times, and to design transparent processes that are more manageable and perceivable.

The main effects that TTP has on construction projects are the improvement of the workflow and the decrement of all types of wastes. Balancing the sequence duration consists of improving the productivity of the slower work chunks. This is done mainly by allocating more resources or by assessing the processes itself. In the long run, all the processes' duration improves as all the trades perform the same tasks in different areas and comparable quantities.

The short cycle times make the implementation process more manageable and decrease the Work-In-Progress (WIP) as the project management team identifies who is working, when, and where. The Takt time is a milestone for each working crew, and it is stabilization for all the operational processes. Setting an even duration for all the activities, exact locations, and precise movement path for the trades avoids the overproduction and optimizes the logistics.

Optimizing the supply chain determines the inventory capacities of the sites. This results in less waiting times for the crews. However, the level of information in the TTP schedule is considerable, and it is challenging to transmit it in real-time. For this reason, training, different tools, and on-site proactivity are required. In Takt Control, aligning and continuously supporting all the perspectives of production is of crucial importance.

Succeeding with TTP is highly dependent on the collaboration between all the participants. The broad cooperation extinguishes the barriers of TTP implementation and orients all the teams to a common aim. The contractors decide the duration of their activities and commit to their decisions. Collaborative meetings are held regularly during the whole implementation period, which ensures the production stability criteria. These meetings also enable the discussion between the successive crews about various problems and expectations.

In TTP, by contrast with other scheduling techniques, the time and space buffer, which are mechanisms to optimize the schedule, are replaced by the capacity buffer. In other words, the capacity buffer is considered the time in disposition for trades that perform their task faster than the Takt. Theoretically, this is regarded as time waste. However, practically on-site occur many unplanned activities and processes in which the resources involve their respective tasks. The time buffer in TTP can be considered an empty wagon of the train, indicating a waiting time when the drying period is necessary.

The case studies conducted in this thesis illustrate that the project delivery time is decreased in all the cases, presenting a structured method of implementing TTP in all the stages of the project. Improving the production rates of slower tasks, as illustrated in the literature review chapters, in many cases, requires increasing the number of resources. This indicates that the costs associated with TTP increase. However, the labor cost increment is balanced by slowing down the faster activities to align the Takt. In addition, the project cost is directly linked with the construction's duration. The duration's overall reduction, committing to reach the required quality and avoid redo, avoiding overproduction, and involving all the participants in the decision making, results in overall cost reduction.

The barriers to reaching the required quality in TTP are illustrated in the Toyota Production System and adapted in construction projects. Therefore, considering that this scheduling technique is used to add value to all the processes, in cases when different methods and means cannot reach the quality, the production system should stop in that specific area, so the particular activity reaches the required level of quality.

The mechanisms used to increase the quality of the plan and the deliverables include different natures of training, usage of various tools, incentive type of contracts, and testing options before the implementation to set the common ground of works. The use of BIM since the early stages of the project facilitates the overall TTP implementation process. Incentive contractual agreements are also necessary though it contradicts the social collaboration aspect in which TTP relies upon. The test of the schedule, before the construction starts, is the last step of optimization regarding pre-construction stages.

The interior works present more improvement potential as the repetitiveness factor and the flexibility of Takt zones are higher. However, all the processes of construction have repetitiveness, and TTP is possible to be implemented in all kinds of construction works.

8.1 Recommendations for future research

There are a number of gaps that follow the findings of this research which would evaluate realistically the implementation framework proposed in this thesis:

- What are the cost/benefit ratio of the early preparations for TTP implementation?
- What is the organisational structure that should follow up with the broad participation of all the project members, and the feasibility aspect of such a managerial structure?
- What is the minimum project scale for a positive TTP impact in terms of time and quality according to the proposed framework?
- What is the risk of using incentive form of contracts for all the type of contracted works and what are the alternative risk mitigation measures to motivate all the participants to commit to the plan?
- What BIM level of detail is required to avoid overproduction of information, and cost feasibility of using BIM and the TTP testing options for every project?

Declaration of Authorship

I hereby declare that the attached Master's thesis was completed independently and without the prohibited assistance of third parties, and that no sources or assistance were used other than those listed. All passages whose content or wording originates from another publication have been marked as such. Neither this thesis nor any variant of it has previously been submitted to an examining authority or published.

Berlin, 27.10.2020

Location, Date

Signature of the student

References

Al Sarraj, Z. M. (1990) ‘Formal Development of Line-of-Balance Technique’, *Journal of Construction Engineering and Management*, vol. 116, no. 4, pp. 689–704.

Alarcòn, L., ed. (1997) *Lean Construction* [Online], New York, Taylor & Francis. Available at https://books.google.de/books?id=tUpZDwAAQBAJ&printsec=frontcover #v=onepage&q&f=false (Accessed 10 August 2020).

Arditi, D. and Albulak, M. Z. (1986) ‘Line-of-Balance Scheduling in Pavement Construction’, *Journal of Construction Engineering and Management*, vol. 112, no. 3, pp. 411–424.

Arditi, D., Tokdemir, O. B. and Suh, K. (2001) ‘Effect of learning on line-of-balance scheduling’, *International Journal of Project Management* [Online]. Available at https://
d1wqtxts1xzle7.cloudfront.net/51343264/s0263-7863_2899_2900079-420170113-
20710-h2pyko.pdf?1484346403=&response-content-disposition=inline%3B+file-
name%3DEffect_of_learning_on_line_of_balance_sc.pdf&Expires=1597244365&Sig-
nature=gVCxkdCqDW-gILstUpL6L9-gMZc-
dyfnDz5Gwa~jiWk8Db3yt5aPhRXRLaF4tz7ksLb~q31qt1SYS-
jPjCWsNCBhapdI8gJLI5jsA0bF0NZ29jX8gxnvIJLBv9BGcR3nq-HG9asNGgTSSPle-
RaRswDkmNIQsMFhcgECBVHhsZ~z84koOfksQHLV1snuYzB39pev2RNXxT9SImJ-
PGVJRoO~ZxqkSp1VO7d85MPJ5uCo84GDm-9xbjBJLUtf66uj0DxE~Nj3-
FOjdXh89rIvDLTxeDcGDV8pZBUzB9eIMlo4TkbkWip0bA-
AA0KJFD4S67weMaltdUFfMeuidQJr5~9w__&Key-Pair-Id=APKAJ-
LOHF5GGSLRBV4ZA (Accessed 12 August 2020).

Arumugam, M. (2018) *Resource Leveling and Resource Smoothing Explained with an Example* [Online], PM Drill. Available at https://www.pmdrill.com/resource-leveling-smoothing-explained/ (Accessed 23 August 2020).

Aziz, R. F. and Hafez, S. M. (2013) ‘Applying lean thinking in construction and performance improvement’, *Alexandria Engineering Journal*, vol. 52, no. 4.

Ballard, G. (1999) ‘Work Structuring: LCI White Paper - 5’, *Lean Construction Institute* [Online]. Available at https://www.leanconstruction.org/media/library/id48/Work_Structuring.pdf (Accessed 12 July 2020).

Ballard, G. and Howell, G. (2003) ‘Lean project management’, *Building Research & Information*, vol. 31, no. 2, pp. 119–133.

Ballard, G. and Tommelein, I. (1999) ‘Aiming for Continuous Flow: LCI White Paper-3’, *Lean Construction Institute* [Online]. Available at http://courses.engr.uky.edu/CE/ce699/LCI%20White%20Papers/4%20WP3-ContinuousFlow.pdf (Accessed 12 July 2020).

Ballard, H. G. (2000a) *The Last Planner System of Production Control*, Dissertation, Birmingham, England, University of Birmingham [Online]. Available at https://etheses.bham.ac.uk/id/eprint/4789/ (Accessed 11 August 2020).

Ballard, H. G. (2000b) *The Last Planner System of Production Control*, Dissertation, U.K., University of Birmingham [Online]. Available at https://etheses.bham.ac.uk//id/eprint/4789/1/Ballard00PhD.pdf (Accessed 18 August 2020).

Bertelsen, S. and Koskela, L. (2002) ‘Managing the three aspects of production in construction’, *International Group for Lean Construction*, vol. 10 [Online]. Available at https://www.researchgate.net/profile/Lauri_Koskela/publication/228608933_Managing_the_three_aspects_of_production_in_construction/links/0fcfd5081aa832ecd1000000/Managing-the-three-aspects-of-production-in-construction.pdf (Accessed 14 June 2020).

Best, R., Valence, G. de and Langston, C. (2002) *Design and construction: Building in value* [Online], Oxford, London, Butterworth-Heinemann. Available at http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10186557.

Binninger, M., Dlouhy, J. and Haghsheno, S. (2017) ‘Technical Takt Planning and Takt Control in Construction’, *25th Annual Conference of the International Group for Lean Construction.* Heraklion, Greece, 7/9/2017 - 7/12/2017, International Group for Lean Construction, pp. 605–612.

Binninger, M., Dlouhy, J., Steuer, D. and Haghsheno, S. (2017) ‘Adjustment Mechanisms for Demandoriented Optimisation in Takt Planning and Takt Control’, *25th Annual Conference of the International Group for Lean Construction.* Heraklion, Greece, 7/9/2017 - 7/12/2017, International Group for Lean Construction, pp. 613–620.

Boldt (2012) *Sutter Health - Woman's and Children's Center* [Online]. Available at https://www.theboldtcompany.com/projects/ilpd/sutter-health-woman-s-and-children-s-hospital (Accessed 1 September 2020).

Brioso, X., Murguia, D. and Urbina, A. (2017) 'Comparing three scheduling methods using BIM models in the Last Planner System', *Organization, Technology and Management in Construction: an International Journal*, vol. 9, no. 1, pp. 1604–1614.

Burghate, N. (2018) 'Work Breakdown Structure: Sipmlyfying Project Management', *International Journal of Commerce and Management Studies (IJCAMS)*, vol. 3 [Online]. Available at https://www.ijcams.com/wp-content/uploads/2018/06/WBS.pdf (Accessed 23 August 2020).

Callahan, M. T., Quackenbush, D. G. and Rowings, J. E. (1992) *Construction project scheduling*, New York, McGraw-Hill.

Clough, R. H., Sears, G. A. and Sears, S. K. (2000) *Construction project management, 4th ed*, New York, Wiley.

Cohen, E. (2018) *How to Use the Critical Path Method for Complete Beginners* [Online], workamajig. Available at https://www.workamajig.com/blog/critical-path-method (Accessed 24 August 2020).

Construction Industry Institute (2007) *Roadmap for Lean Implementation at the Project Level,* Construction Industry Institute, CII Research Report 234-11 [Online]. Available at https://www.researchgate.net/profile/Glenn_Ballard/publication/232322523_Roadmap_for_Lean_Implementation_at_the_Project_Level/links/00b7d52011d137218e000000.pdf (Accessed 10 August 2020).

Dlouhy, J., Binninger, M., Oprach, S. and Haghsheno, S. (2017) 'Three-Level Method of Takt Planning and Takt Control: A new approach for designing production systems in construction', *24th Annual Conference of the International Group for Lean Construction, Boston, USA*, vol. 24, pp. 13–22 [Online]. Available at https://pdfs.semanticscholar.org/817c/17ef1473d18351eccfd3c6f3bd5f23dd5279.pdf (Accessed 2 September 2020).

Eesti Timmitud Ehituse Tugirühm (2016) *VII Projektijuhi päev: Meeli Linnik* [Online], Tallin, Estonia. Available at https://www.youtube.com/channel/UCP-0kQ0nqcV0-WZz0ThMCMQ (Accessed 31 August 2020).

Frandson, A. and Tommelein, I. D. (2014) ‘Development of a Takt-time Plan: A Case Study’, *Construction Research Congress 2014: Construction in a Global Network.* Atlanta, Georgia, May 19-21, 2014. [Place of publication not identified], American Society of Civil Engineers, pp. 1646–1655.

Frandson, A. G. (2019) *Takt time planning as a work structuring method to improve the construction work flow*, Dissertation, UC Berkeley [Online]. Available at https://escholarship.org/uc/item/6dp4n4fz (Accessed 11 August 2020).

Frandson, A. G., Berghede, K. and Tommelein, I. (2013) ‘Takt Time Planning for Construction of Exterior Cladding’, *Proceedings 21st Annual Conference on International Group for Lean Construction (IGLC 21), Brazil* [Online]. Available at http://iglc.net/Papers/Details/902 (Accessed 17 August 2020).

Frandson, A. G., Berghede, K. and Tommelein, I. (2014) ‘Takt-Time Planning and the Last Planner’, *Proceedings 21st Annual Conference on International Group for Lean Construction, Oslo, Norway(IGLC 22)* [Online]. Available at http://iglc.net/Papers/Details/1063 (Accessed 18 August 2020).

Frandson, A. G., Seppänen, O. and Tommelein, I. (2015) ‘Comparison Between Location-Based Management and Takt Time Planning’, *International Group for Lean Construction*, pp. 3–12 [Online]. Available at www.iglc.net (Accessed 15 August 2020).

Gardarsson, M. H., Lædre, O. and Svalestuen, F. (2019) ‘Takt Time Planning in Porsche Consulting, the Boldt Company and Veidekke’, *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC).* Dublin, Ireland, 7/3/2019 - 7/5/2019, International Group for Lean Construction, pp. 551–562.

Haghsheno, S., Binninger Marco, Dlouhy, J. and Sterlike, S. (2016) ‘History and Theoritical Foundations of Takt Planning and Takt Control’, *24th Annual Conference of the International Group for Lean Construction, Boston, USA*, pp. 53–62 [Online]. Available at http://iglc.net/Papers/Details/1297 (Accessed 17 August 2020).

Hajdu, M. (2015) ‘Point-to-point Versus Traditional Precedence Relations for Modeling Activity Overlapping’, *Procedia Engineering*, vol. 123, pp. 208–215.

Heinonen, A. and Seppänen, O. (2016) ‘Takt Time Planning in Cruise Ship Cabin Refurbishment:: Lessons for Lean Construction’, *Proceeding 24th Annual Conference of*

International Group for Lean Construction, Boston, MA, USA, pp. 23–32 [Online]. Available at http://iglc.net/Papers/Details/1338 (Accessed 17 August 2020).

Hendrickson, C. and Au, T. (2008, 1998) *Project management for construction: Fundamental concepts for owners, engineers, architects, and builders*, 2nd edn, Pittsburgh, Penn., Carnegie Mellon University.

Hjelmbrekke, H., Hansen, G. K. and Lohne, J. (2015) 'A Motherless Child–Why do Construction Projects Fail', *Procedia Economics and Finance*, vol. 21, pp. 72–79.

Howell, G. A., ed. (1999) *What is Lean Construction* [Online]. Available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.418.4301&rep=rep1&type=pdf#page=9 (Accessed 10 August 2020).

Kaliba, C., Muya, M. and Mumba, K. (2009) 'Cost escalation and schedule delays in road construction projects in Zambia', *International Journal of Project Management*, vol. 27, no. 5, pp. 522–531 [Online]. DOI: 10.1016/j.ijproman.2008.07.003.

Kankainen, J. and Seppänen, O. (2003) 'A Line-of-balance based Schedule Planning and Control System', p. 3.

Kenley, R. and Seppänen, O. (2009) *Location-based management system for construction: Improving productivity using Flowline*, London, Spon Press.

Kerzner, H. (2003) *Project management a systems approach to panning, scheduling, and controlling*, 8th edn, New Jersey, John Wiley & Sons.

Kidston, P. and Haward, K. (2015) *Planning, scheduling, monitoring and control: The practical project management of time, cost and risk*, Princes Risborough, Buckinghamshire, Association For Project Management.

Kischk, M., Al-Hajj, A., Pollock, R. and Aouad, G. (2002) 'A Practical Cost Breakdown Structure for Effective Whole-life Costing of Build Assets' [Online]. Available at https://www.irbnet.de/daten/iconda/CIB16810.pdf (Accessed 25 August 2020).

Klein, R. (2000) *Scheduling of resource-constrained projects*, Boston, Kluwer Academic Publishing.

Koskela, L. (1992) 'Application of the new Production Philosophy to Construction', *Center for Integrated Facility Engineering* [Online]. Available at https://www.leanconstruction.org/media/docs/Koskela-TR72.pdf (Accessed 7 September 2020).

Koskela, L. (2000) *An exploration towards a production theory and its application to construction*, Espoo, Technical Research Centre of Finland.

Koskela, L., Ballard, G., Howell, G. and Tommelein, I. (2002) 'The foundations of Lean Construction' [Online]. Available at https://www.researchgate.net/publication/28578914_The_foundations_of_lean_construction (Accessed 4 September 2020).

Koskela, L., Howell, G., Ballard, G. and Tommelein, I. 'The foundations of lean construction: Editorial Comment, chapters 14-15', 213,215,217 [Online]. Available at https://www.researchgate.net/profile/Glenn_Ballard/publication/28578914_The_foundations_of_lean_construction/links/0deec52d174073ac8a000000.pdf (Accessed 10 August 2020).

Lander, E. and Liker, J. K. (2007) 'The Toyota Production System and art: making highly customized and creative products the Toyota way', *International Journal of Production Research*, vol. 45, no. 16, pp. 3681–3698.

Lean Enterprise Institute (2015) *A Brief History of Lean* [Online], Lean Enterprice Institute. Available at https://www.lean.org/whatslean/history.cfm (Accessed 17 August 2020).

Lean IPD (n.d) *Lean and Integrated Project Delivery* [Online]. Available at https://leanipd.com/ (Accessed 1 September 2020).

Lehtovaara, J., Mustonen, I., Peuronen, P., Seppänen, O. and Peltokorpi, A. (2019) 'Implementing Takt Planning and Takt Control Into Residential Construction', *Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC).* Dublin, Ireland, 7/3/2019 - 7/5/2019, International Group for Lean Construction, pp. 417–428.

Liker, J. K. (2004) *The Toyota way*, New York, McGraw-Hill.

Linnik, M. (2016) *Lean and Takt Time Planning at Hospital Project in San Francisco* [Online], Tallin, Estonia. Available at https://www.tktk.ee/wp-content/uploads/Meeli_takt_time_planning.pdf (Accessed 1 September 2020).

Linnik, M., Berghede, K. and Ballard, G. (2013) 'An Experiment in Takt Time Planning Applied to Non-Repetitive Work', *Proceedings 21st Annual Conference on International Group for Lean Construction (IGLC 21)* [Online]. Available at http://iglc.net/Papers/Details/924 (Accessed 20 August 2020).

Lu Ming and Li Heng (2003) 'Resource-Activity Critical-Path Method for Construction Planning', *Journal of Construction Engineering and Management*, vol. 129, no. 4, pp. 412–420.

Melzner, J. (2019) 'BIM-based Takt-Time Planning and Takt Control: Requirements for Digital Construction Process Management', *36th International Symposium on Automation and Robotics in Construction (ISARC 2019)* [Online]. Available at https://www.iaarc.org/publications/fulltext/ISARC_2019_Paper_9.pdf (Accessed 22 August 2020).

Mendes, R., JR. and Heineck, L. F. M. (1998) 'Preplaning Method for Multi-Story Building Construction using Line of Balance', *Proceedings IGLC 98*, pp. 4–8 [Online]. Available at https://www.researchgate.net/profile/Olli_Seppaenen/publication/305873584_A_LINE-OF-BALANCE_BASED_SCHEDULE_PLANNING_AND_CONTROLLING_SYSTEM/links/592bac94458515e3d46cab8c/A-LINE-OF-BALANCE-BASED-SCHEDULE-PLANNING-AND-CONTROLLING-SYSTEM.pdf (Accessed 13 August 2020).

Millstein, M. A. and Martinich, J. S. (2014) 'Takt Time Grouping: implementing kanban-flow manufacturing in an unbalanced, high variation cycle-time process with moving constraints', *International Journal of Production Research*, vol. 52, no. 23, pp. 6863–6877.

Motzko, C., ed. (2013) *Praxis des Bauprozessmanagements: Termine, Kosten un Qualität zuverlässig steuern*, Berlin, Ernst & Sohn.

Mubarak, S. (2010) *Construction Project Scheduling and Control, 2nd Edition*, 2nd edn, John Wiley & Sons.

NEALE, R. H. and NEALE, D. E. (1989) *Construction Planning: Engineering Management*, Thomas Telford.

Olivieri, H., Seppänen, O. and Denis Granja, A. (2018) 'Improving workflow and resource usage in construction schedules through location-based management system (LBMS)', *Construction Management and Economics*, vol. 36, no. 2, pp. 109–124.

Ōno, T. and Bodek, N. (1988) *Toyota production system: Beyond large-scale production*, New York, Productivity Press.

Picchi, F. A. and Granja, A. D. (n.d.) ‘Construction Sites: Using Lean Principles to Seek Broader Implementation’ [Online]. Available at https://pdfs.semanticscholar.org/4207/92bcd2316b95e15203f102569c9e1719a314.pdf (Accessed 15 July 2020).

PMI (2017) *A guide to the project management body of knowledge (PMBOK guide)* [Online], Newtown Square, PA, Project Management Institute. Available at https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5180849.

Refine Projects (2019) *A better way to work - The Last Planner System* [Online], Internet. Available at https://refineprojects.com/blog/lean-refine/a-better-way-to-work-the-last-planner-system/.

Rezaei, A. (2015) ‘Location Based Scheduling In The Form Of Flow Line and Its Comparison to Cpm/Bar Chart Scheduling’, *International Journal of Electronics, Mechanical and Mechatronics Engineering*, vol. 5, pp. 891–903 [Online]. Available at https://pdfs.semanticscholar.org/2d24/64486df6a7d824858df676b3e2068e569b26.pdf (Accessed 15 June 2020).

Sacks, R., Koskela, L., Dave, B. A. and Owen, R. (2010) ‘Interaction of Lean and Building Information Modeling in Construction’, *Journal of Construction Engineering and Management*, vol. 136, no. 9, pp. 968–980.

Sacks, R. and Partouche, R. (2010) ‘Empire State Building Project: Archetype of “Mass Construction”’, *Journal of Construction Engineering and Management*, vol. 136, no. 6, pp. 702–710.

Seppänen, O. (2009) *Empirical Research on the success of production control in building construction projects*, Dissertation, Helsinki, Helsinki University of Technology [Online]. Available at https://aaltodoc.aalto.fi/bitstream/handle/123456789/4668/isbn9789522480613.pdf?sequence=1 (Accessed 15 August 2020).

Seppänen, O., Ballard, G. and Pesonen, S. (2010) ‘The Combination of Last Planner System and Locaction-Based Management System’, *Lean Construction Journal*, pp. 43–54 [Online]. Available at https://www.leanconstruction.org/media/library/id47/The_Combination_of_Last_Planner_System_and_Location-Based_Management_System.pdf (Accessed 15 August 2020).

Seppänen, O., Evinger, J. and Mouflard, C. (2014) ‘Effects of the location-based management system on production rates and productivity’, *Construction Management and Economics*, vol. 32, no. 6, pp. 608–624.

Seppänen, O. and Kenley, R. (2009) ‘Location-based Management of Construction Projects: Part of a new Typology for Project Scheduling Methodologies: December 13 - 16, 2009, Austin, Texas, U.S.A. ; inclusion of MASM (Modeling and analysis of semiconductor manufacturing)’.

Shingō, S. (1998) *Non-stock production: The Shingo system for continuous improvement*, Portland, Or., Productivity Press.

Snøhetta (2017) *University of Bergen, Faculty of Fine Art, Music and Design (KMD)* [Online]. Available at https://snohetta.com/projects/351-university-of-bergen-faculty-of-fine-art-music-and-design-kmd (Accessed 24 August 2020).

Statsbygg (2017a) *Lean Construction, a breef overview: KHiB, booklet #1* [Online]. Available at https://www.statsbygg.no/globalassets/files/prosjekter/khibergen/lean-hefter/1-leanconstruction.pdf (Accessed 4 September 2020).

Statsbygg (2017b) *Lean Design, a brief overview.: KHiB, booklet #4* [Online]. Available at https://www.statsbygg.no/globalassets/files/prosjekter/khibergen/leanhefter/4-lean-design.pdf (Accessed 25 August 2020).

Statsbygg (2017c) *Lean Strategy, a brief overview: KHiB, booklet #3* [Online]. Available at https://www.statsbygg.no/globalassets/files/prosjekter/khibergen/leanhefter/3-leanstrategy.pdf (Accessed 4 September 2020).

Tommelein, I. D. (2017) ‘Collaborative Takt Time Planning of Non-Repetitive Work’, *25th Annual Conference of the International Group for Lean Construction.* Heraklion, Greece, 7/9/2017 - 7/12/2017, International Group for Lean Construction, pp. 745–752.

Tommelein, I. D., Riley, D. R. and Howell, G. A. (1999) ‘Parade Game: Impact of Work Flow Variability on Trade Performance’, *Journal of Construction Engineering and Management*, vol. 125, no. 5, pp. 304–310.

Tsao, C. C.Y. (2005) *Use of Work Structuring to Increase Performance of Project-Based Production Systems*, Dissertation, University of California, Berkeley [Online]. Available at http://leanconstruction.org.uk/media/docs/2005-Tsao-PhD.pdf (Accessed 18 August 2020).

Tsao, C. C.Y., Tommelein, I., Swanlund, E. and Howell, G. A. (2000) 'Case Study for Work Structuring: Installation of Metal Door Frames', *Proceeding 8th Annual Conference of International Group for Lean Construction, Brighton, U.K* [Online]. Available at http://iglc.net/Papers/Details/125 (Accessed 18 August 2020).

Wertebach, S., Johansen, P. R. and Holm, H. T. (2017) *A Lean and Agile Approach to design and construction* [Online], Birmingham, England. Available at https://leanconstruction.org.uk/wp-content/uploads/2018/09/A-Lean-and-Agile-approach-to-design-and-construction-Holm-Wertebach-Johansen.pdf (Accessed 4 September 2020).