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A Framework for the Implementation of Takt Time in High-Variety, Low-Volume Manufacturing Environments

June 2019

NTNU
Norwegian University of Science and Technology

Master's thesis

Master's thesis

2019

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Submission date: June 2019

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Acknowledgements

This thesis concludes my Master of Science in Global Manufacturing Management at the department of Mechanical and Industrial Engineering, at the Norwegian University of Science and Technology (NTNU) in Trondheim.

It also represents the ending of several years of study. And what a journey it has been. I am grateful for everything I have learned and for all the people I have met in the process. I am truly privileged!

To my supervisor Erlend Alfnes (NTNU), and co-supervisors Kristina Kjersem (Møreforsking AS) and Swapnil Bhalla (NTNU), thank you! Thank you for spending your valuable time on me. Thank you for your critical and constructive (and sometimes terrifying) feedbacks. Thank you for inspiring me and supporting me. I could not have asked for better supervisors.

To the case companies. Thank you for your valuable contribution to my thesis, and the opportunity to learn from you. Thank you for the hospitality and friendliness when we met, in my view you represent the crème de la crème of Norwegian industry.

To my friends and fellow students, especially my fellow office-mates Johanne, Mads and Yan. Thank you for this time we have shared together, with all its' joy, procrastination and despair, but mostly joy. I guess things could have been more productive without the unintentional extensions of lunch-breaks, or the frequent games of ping-pong. But it would have been a lot less rewarding.

Finally, to my family. It is rather difficult to describe how it feels to have someone who's got your back, no matter what. You have always cheered for me, and I have always found strength and motivation in your support. You are the dearest I have, thank you!

Trondheim, 2019

Hallvard Øystese

Summary

High-variety, low-volume (HVLV) supply chains are getting more and more important, as HVLV manufacturers produce customized products in wide varieties that are increasingly demanded by customers. To provide these type of products requires flexibility and responsiveness, which can cause challenges related to turbulence, i.e. unpredictable changes in the value chain that causes variability in production environments, e.g. for product mix, volume and cycle times. Lead time is often a strategic priority for HVLV manufacturers, and improving efficiency is imperative to remain competitive. But being efficient and flexible simultaneously is challenging, and the emergence of lean manufacturing has led to an increased interest in which of its' elements can improve efficiency for HVLV manufacturers.

Takt time is a production control principle that sets the pace for production. Even though it originates from repetitive manufacturing environments, several examples have shown that takt time can be implemented in HVLV manufacturing environments with considerable benefits in efficiency. But literature on takt time in HVLV manufacturing is scarce, and it is not clear how it should be implemented and what environmental characteristics that enables the use of takt time.

The objective of this research is to develop a framework that can support HVLV manufacturers to adopt takt time as a measure to improve manufacturing efficiency, and to facilitate for further empirical studies on takt time in HVLV production environments. To reach this objective, this research will investigate how takt time can be systematically implemented in HVLV manufacturing environments, and to identify characteristics of manufacturing environments that can support the use of takt time.

This research was conducted through a literature study and case study. The literature study was done to provide the fundament of the research, and the description of the problem. Main elements and characteristics of HVLV manufacturing was identified. Fundamentals of takt time were explained, and concepts related to how takt time can be implemented in HVLV manufacturing was identified. In addition, four examples of takt time implementation in HVLV manufacturing was characterised to identify variables that influence the applicability of takt time.

The case study was done to investigate how two case companies implemented takt time in their HVLV manufacturing environments. Concepts that was used in the implementation of takt time were identified, and the manufacturing environments where characterised to

understand why they implemented takt time. In addition, a variability analysis was conducted for both case companies to see how a takt time could be determined.

In this research a framework for the implementation of takt time in HVLV manufacturing environments was presented as the main result. It consists of four phases that suggests which information to collect, how the applicability of takt time can be assessed, and various concepts that can be used to configure the takt time based production, and to determine a takt time.

The research provided two main contributions to theory and practice. 1) The framework provides a systematic methodology that can support practitioners in HVLV manufacturing in the implementation of takt time. A variety of concepts are included, which corresponds to the diversity of HVLV manufacturing. This can further expand the pool of empirical data on which further empirical research can be conducted. 2) The framework provides the means for practitioners of HVLV manufacturing to assess the applicability of takt time for a manufacturing environment.

It was concluded that takt time can be applied in a variety of HVLV manufacturing environments, but that a homogeneous manufacturing mix is important for the applicability of takt time. The various concepts included in the framework are not universally applicable to all HVLV manufacturing environments, and the appropriate composition is likely to vary from case to case. This includes how a takt time can be determined. In general, three guidelines are recommended: 1) avoid fluctuations in takt time, 2) set takt time high enough to buffer against some variability in cycle times, and 3) set takt time low to increase discrepancies and stimulate improvement.

Samandrag

Verdikjeder med høg produktvariasjon og lave produksjonsvolum (HVLV) blir stadig viktigare då HVLV-produsentar lagar spesialtilpassa produkt i mange variantar som i aukande grad blir etterspurde i marknaden. For å kunne tilby slike produkt, krevst det fleksibilitet og evne til respons. Dette kan skape utfordringar relatert til turbulens, dvs. uføreseielege endringar i verdikjeda som skapar variasjon i produksjonsmiljø – for eksempel i produksjonsmiks, volum og prossesseringtider. Leietid er ofte ein strategisk prioritet for HVLV-produsentar, og betring av effektivitet er kritisk for å vere konkurransedyktig. Men, å vere effektiv og fleksibel samtidig er utfordrande, og populariseringa av Lean-produksjon har ført til auka interesse for kva for Lean-element som kan betre effektiviteten for HVLV-produsentar.

Takt-tid er eit prinsipp for produksjonskontroll som avgjer tempoet for produksjon. Sjølv om takt-tid kjem frå repetitive produksjonsmiljø, har fleire eksempel vist at takt-tid kan implementerast i HVLV-produksjonsmiljø og kan betre effektiviteten. Men det er lite i faglitteraturen om takt-tid i HVLV-produksjonsmiljø, og det er ikkje tydeleg korleis takt-tid kan implementerast, og kva for eigenskaper som mogleggjer takt-tid i HVLV-produksjonsmiljø.

Målet med denne studien var å utvikle eit rammeverk som kan støtte HVLV-produsentar til å nytte takt-tid som eit tiltak for å betre effektivitet, og å legge til rette for vidare empirisk studie på takt-tid i HVLV-produksjonsmiljø. For å nå dette målet vil dette studiet undersøke korleis takt-tid kan systematisk implementerast i HVLV-produksjonsmiljø, og å identifisere eigenskaper ved produksjonsmiljøa som legg til rette for bruk av takt-tid.

Studien blei gjort gjennom litteratur- og case-studie. Litteraturstudiet blei gjort for å danne grunnlaget for forskinga og problembeskrivinga. Hovudelementa og eigenskaper ved HVLV-produksjon blei identifiserte. Det grunnleggjande ved takt-tid blei forklart, og konsept knytta til korleis takt-tid kan implementerast blei identifiserte. I tillegg blei fire eksempel på implementering av takt-tid i HVLV-produksjon karakterisert for å identifisere variablar som påverkar anvendelegheita av takt-tid.

Case-studien blei utførd for å undersøke korleis to case-bedriftar implementerte takt-tid i HVLV-produksjonsmiljø. Konsept som blei brukt i implementeringa blei identifisert og produksjonsmiljøa blei karakterisert for å forstå kvifor dei kunne implementere takt-tid. I

tillegg blei det gjort ein variasjonsanalyse for begge case-bedriftene for å sjå korleis ein takt-tid kan bestemmast.

I denne studien blei eit rammeverk for implementering av takt-tid i HVLV-produksjonsmiljø presentert. Den består av fire fasar som foreslår kva for informasjon som skal samlast, korleis anvendelegheita av takt-tid kan vurderast, og ulike konsept som kan brukast til å konfigurere takt-tidbasert produksjon og å bestemme ein takt-tid.

Studien ga to hovudbidrag til teori og praksis: 1) Rammeverket gir ein systematisk metode som kan støtte HVLV-produsentar i implementering av takt-tid. Ei rekkje konsept er inkludert som svarar til mangfaldet i HVLV-produksjon. Dette kan utvide basen av empiriske data som kan forskast vidare på. 2) Rammeverket gir HVLV-produsentar midlar til å vurdere kor brukbar takt-tid er i deira produksjonsmiljø.

Det blei konkludert at takt-tid kan brukast i eit variert utval HVLV-produksjonsmiljø, men at ein homogen produksjonsmiks er viktig for at takt-tid skal vere brukbar. Dei ulike konsepta som inngår i rammeverket kan ikkje brukast generelt for alle HVLV-produksjonsmiljø, og kva som er ei plausibel samansetting vil variere frå tilfelle til tilfelle. Dette inkluderer også korleis ein bestemmer ei takt-tid. I denne studien blei det anbefalt tre retningslinjer: 1) Unngå svingingar i takt-tid, 2) set takt-tida så høg at ein har ein buffer mot variasjon i prossesseringstider, og 3) sett takt-tida lågt nok til å auke avvik og stimulere betring.

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Abbreviations

ATO – Assemble-to-Order

BOM – Bill of Material

CODP – Customer Decoupling Point

CONWIP – Constant Work in Progress

CPI – Cost Performance Index

ETO – Engineer-to-Order

EVM – Earned Value Management

FIFO – First-In-First-Out

HVLV – High-Variety, Low-Volume

JIT – Just-In-Time

LPP – Lean Project Planning

LPS – Last Planner® System

MTO – Make-To-Order

MTS – Make-To-Stock

NDT – Non Destructive Testing

PDCA – Plan Do Check Act

PPC – Percent Planned Complete

SPI – Schedule Performance Index

TTG – Takt Time Grouping

WIP – Work In Progress

1 Introduction

1.1 Background

The demand for customized products is increasing (Strandhagen et al., 2018), and as a result, high-variety, low-volume (HVLV) supply chains are becoming increasingly important (Gosling and Naim, 2009, Stevenson et al., 2005). HVLV manufacturing is based on delivering a wide variety customized products (Katic and Agarwal, 2018, Adrodegari et al., 2015). Designing and producing highly customized products requires flexibility and involves long lead times (Rauch et al., 2015). Increased competition and customer expectations implies challenges that calls for improved efficiency and competitiveness (McDonald et al., 2002). Improving operational efficiency and simultaneously providing flexibility for customers while achieving organizational ambidexterity, carries significant challenges for HVLV manufacturers, because the flexibility causes variability in production (Katic and Agarwal, 2018). Manufacturing efficiency is key to remain competitive (Ricondo Iriondo et al., 2016). And the emergence of lean manufacturing has led to an increased interest on which elements from lean manufacturing might improve efficiency for HVLV manufacturers (Jina et al., 1997).

Takt time developed as a central element in the just-in-time pillar of the Toyota Production System, the precursor to lean manufacturing. It aimed to control the pace of production, by matching the production rate with the demand rate (Ricondo Iriondo et al., 2016, Chapman et al., 2017). It has traditionally been associated with lean manufacturing with repetitive production processes (Haghsheno et al., 2016). Nevertheless, the use of takt time has entered environments with non-repetitive production. In lean construction, takt time planning has provided considerable benefits such as lead-time reduction (Heinonen and Seppänen, 2016, Yassine et al., 2014, Linnik et al., 2013), reduction of work-in-progress (WIP) (Faloughi et al., 2015, Mariz et al., 2012), and identification of problems (Vatne and Drevland, 2016, Chauhan et al., 2018). Similar benefits have been found for takt time application in several HVLV manufacturing environments. Ricondo Iriondo et al. (2016) found that takt time could be applied to a significant part of the production process for a machine tool manufacturer. Similarly, successful implementation of takt time have been found by Slomp et al. (2009) for a manufacturer of electrical conductor components, and Kjersem et al. (2015) for a shipyard’s assembly line.

The benefit of reducing lead time is interesting for HVLV as lead time is often an important competitive priority (Powell et al., 2014, Stevenson et al., 2005), thus the reduction of it is crucial to improve performance of HVLV companies (Strandhagen et al., 2018, Slomp et al., 2009). Several case studies from lean construction have proven this benefit, some even find that the completion time is more or less halved (Frandson and Tommelein, 2016, Yassine et al., 2014), or reduced as much as 73% (Heinonen and Seppänen, 2016). The same benefits where found for case studies outside the construction industry. For example, Ricondo Iriondo et al. (2016) found that better efficiency was achieved with takt time compared to the formerly approach. In addition, lead time reliability increased from 60% to 75%. The use of takt time aims to stabilize flow which facilitates for continuous improvement (Oluyisola et al., 2016). This flow surfaces issues and problems which can be dealt with in order to reduce wastes, improve operations, hence reducing throughput time (Liker and Meier, 2006).

1.2 Research Problem

Several studies have shown interesting benefits from applying takt time in production. However, the universal applicability of lean and takt time is questionable (Naim and Gosling, 2011, Cooney, 2002). According to Cooney (2002), lean is not universal applicable and argues that it is impossible to establish standard times and achieve production levelling with low volume products and changing production requirements. Elements from lean, such as takt time, are often related to mass production and repetitive manufacturing, such as Make-to-Stock (MTS) supply chains (see section 3.2). In addition, variability is a central challenge for applying lean in HVLV (Alfnes et al., 2016). Lean and takt time have traditionally been effective in eliminating variability through standardization of products and processes. This contradicts with the central principle of HVLV in offering customer-specific products, which makes variability inevitable (Powell and van der Stoel, 2016, Jina et al., 1997). Hence, takt time may seem unfit for HVLV environment.

More empirical research is needed to validate and establish the advantages of takt time based control in HVLV manufacturing environments (Slomp et al., 2009), and to identify which environmental characteristics enables the use of takt time. Research on takt time in HVLV manufacturing environments is scarce (Oluyisola et al., 2016), and the few examples that conveys takt time in HVLV manufacturing do not clarify how it can be implemented, as no standardised methodologies are provided. In addition, takt time calculation is not straight-forward in HVLV settings, and experience sometimes seems to be a driver in the determination of a takt time (Tommelein, 2017). With reducing lead-time as one of its primary goals, takt time could potentially improve the manufacturing efficiency of HVLV organizations, thus improving their competitiveness. A systematic approach for the implementation of takt time in HVLV manufacturing could serve as a reference framework for practitioners in HVLV manufacturing environments to guide the implementation of takt time based production, and the determination of a takt time. This could promote a wider implementation of takt time in HVLV manufacturing, thus expanding the empirical basis that can support empirical research on takt time in HVLV manufacturing. To address this research gap, this research focuses on *how* and *where* takt time can be applied in HVLV manufacturing environments.

1.3 Research Objectives and Research Questions

The objective of the presented research was to develop a framework that can support HVLV manufacturers to adopt takt time as a measure to improve manufacturing efficiency, and to facilitate for further empirical studies on takt time in HVLV production environments. To reach this objective, this research investigated how takt time can be systematically implemented in HVLV manufacturing environments, and to identify characteristics of manufacturing environments that can support the use of takt time.

The research problem and objectives led to the following research questions:

Research question 1: How can takt time based production control be implemented in HVLV manufacturing environments?

> Determination of how the literature suggest to implemented takt time in HVLV environments, and the related concepts that can be applied in the process. Examination of how the case companies implemented takt time, and what considerations they took.

Research question 2: How can takt time be determined for HVLV manufacturing environments?

> Identification of different approaches to determine a takt time in literature. Collection and analysis of data from case studies. Investigation of how mapping variability can aid the determination of takt time definition.

Research question 3: What variables influences the applicability of takt time for HVLV manufacturers?

Determination of characteristics of HVLV manufacturers who have implemented takt time, found in literature and case studies, which indicates whether or not takt time is feasible for implementation.

1.4 Research Scope

The scope of this research is limited to HVLV manufacturers of single-item production characterized with high variability and low volume in demand. Make-to-order (MTO) and engineer-to-order (ETO) are the main manufacturing strategies typically exhibited in HVLV manufacturing environments. Further, the scope is limited to focus on the variability of products in terms of their work content and processing time.

In HVLV companies, two working processes can be distinguished; non-physical, which include engineering, procurement, project management and administrative processes, and physical processes that comprises the manufacturing, assembly and installation of products and components (McGovern et al., 1999). This research focuses on the latter.

1.5 Report Outline

This report is structured into seven chapters, which contains the following:

Chapter 1 – Introduction: This chapter presents the background of this research and explains the problem for which the research aims to address. Then, the research objectives and three research questions are presented before the scope of the research is introduced.

Chapter 2 – Methodology: The literature and research methods used to reach the objectives and answer the research questions are presented and justified, by discussing how and why data was selected, analysed and validated.

Chapter 3 – Theoretical Background: This chapter provides the theoretical fundament of the research, by explaining the related topics. The chapter starts with explaining the fundamental elements and characteristics of HVLV manufacturing environments. Then the concept of takt time is introduced, before different examples of takt time implementation in HVLV manufacturing environments are characterised. Different approaches to determine takt time is explained before different concepts for takt time implementation in HVLV manufacturing environments are presented.

Chapter 4 – Case study: This chapter presents the two cases included in this research. Each case company is introduced before the manufacturing process is explained. Further, it is explained how the case companies implemented takt time, and some aspects of their planning processes.

Chapter 5 – Results: Firstly, a framework for the implementation of takt time in HVLV manufacturing environments is presented. Secondly, the identified concepts from the literature and case study are presented. Thirdly, the findings from the variability analysis of the two case companies are presented. Finally, the characteristics of examples of takt time implementation in HVLV manufacturing environments are presented.

Chapter 6 – Discussion: This chapter contains the discussion on the results presented in the previous chapter. The chapter is structured around the three research questions, before the limitations and weaknesses of the research are discussed.

Chapter 7 – Conclusion: This chapter presents the conclusions of the research, and how it may contribute both to theory and practice. The chapter concludes with suggestions for further research.

2 Methodology

This chapter concerns the methodology used for this research. Methods describes the procedures used to systematically collect data and interpret them in order to solve a problem (Rajasekar et al., 2006, Croom, 2008, Kothari, 2004).

Figure 1 shows a simplified overview of the process of this study. A preliminary literature study was conducted to map state of the art theory, related to takt time in HVLV. This was to identify research gaps and to help define a research scope, explained by Croom (2008) as *research ability*, which establishes the legitimacy and authority of a research. From this the research problem was defined and the research objectives and research questions were constructed, as discussed in the introduction. To reach the research objective, the research methodology was developed with a theoretical and an empirical part consisting of two main research methods; a literature study and a case study, which will be further explained in this chapter. The literature study was used mainly to answer research questions one and two, while the case study contributed to all three research questions.

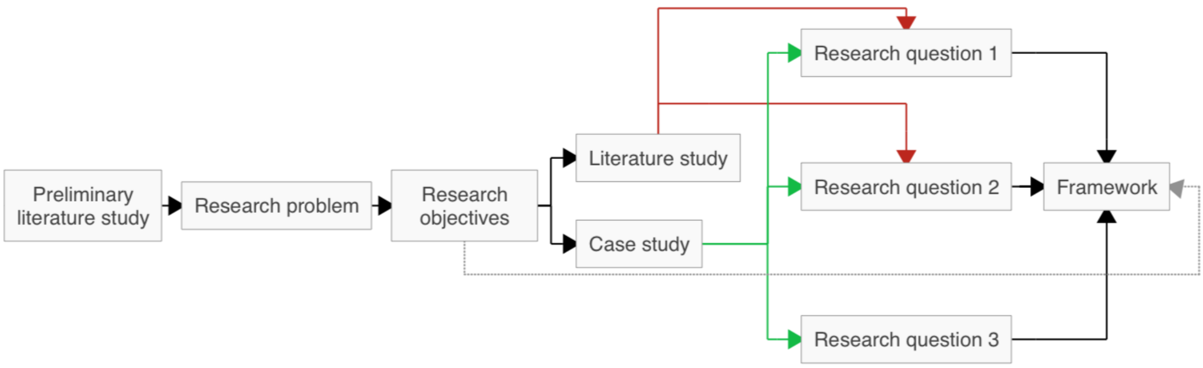

Figure 1: Research process

Qualitative methods were mainly used, but some quantitative research was done to support the qualitative findings. Quantitative research concerns measurement of quantity or amount, while qualitative research relates to quality and typically investigates the *why* and *how* (Rajasekar et al., 2006).

2.1 Literature Study

The literature study was done to provide a theoretical fundament to explain the important topics and terms used in this research. This includes description of the context of the problem, namely the HVLV manufacturing environment, and theory concerning the basics of takt time and takt time in HVLV manufacturing environments. In addition, building new theory relies on past literature (Eisenhardt, 1989), which makes the literature study important to support the case study.

The literature study was conducted similarly to the eight steps suggested by Gough (2007):

1. **Formulate review question and develop protocol:** In this step the research questions and selection of the appropriate methods were identified, as discussed in the beginning of this chapter.
2. **Define studies to be considered:** In this step the inclusion criteria was defined in order to ensure the relevance of the included literature. The literature should fulfil one or more of these criteria: it should 1) address characteristics of manufacturing environments relatable to HVLV, 2) address the application of takt time in HVLV manufacturing, and 3) explain basic concepts relevant to HVLV manufacturing and takt time.
3. **Search for studies:** The literature study was conducted by using random searches, key word searches, block searches as well as cited references search from key articles. Several online databases were used; Oria (NTNU database), Google Scholar, Scopus and the conference paper database from International Group for Lean Construction. Literature from Lean Construction was an important source of information, as it is a large contributor of literature concerning takt time in non-repetitive environments.

Table 1: Keywords used in literature search

Level 1	**Level 2**
Engineer to order/ETO **Make to order/MTO** **Non-repetitive** **Low volume high variability** **High Variability low volume**	Environments Manufacturing Production Characteristics Typology
Takt **Takt time** **Takt time planning** **Takt time control** **Just-in-time/JIT** **Lean**	ETO MTO High variability low volume Low volume high variability Non-repetitive Manufacturing Construction

Table 1 presents the main keywords used in literature search. Level 1 contains the main keywords used to find relevant sources, while the level 2 keywords contains keywords which were used together with the first keywords to narrow down the scope.

The articles found from the literature searches were skimmed before the most relevant articles were selected based on the research objectives and research questions.

4. **Screen studies:** The literature found from the searches was skimmed before the most relevant literature was selected based on the research objectives and research questions.
5. **Describe studies:** By taking notes, the relevant information was assembled from the literature screening. The information was structured into categories that became the foundation for the theoretical background chapter. The data was structured into two main categories; characteristics of HVLV manufacturing, and takt time in HVLV manufacturing. In the latter category, the data was further structured into three sub-categories: takt time fundamentals, empirical studies of takt time in HVLV manufacturing, and concepts of takt time implementation in HVLV manufacturing.
6. **Appraise study quality and relevance:** To ensure the quality of the collected data, scientific literature that was peer reviewed was emphasized. The age of the various texts were also considered in order to ensure its topicality.
7. **Synthesise findings:** In this step the collected data was analysed and connected to the research questions. A framework developed by Buer et al. (2018) was used to characterise HVLV manufacturing and empirical studies related to takt time implementation in HVLV manufacturing. This was done to structure the data and facilitate for comparison. Concepts related to implementation of takt time in HVLV manufacturing were analysed to evaluate their relevance towards the research questions.
8. **Communicate and change:** In this step, the findings were interpreted and synthesized in order to generalize their meaning. This was interconnected with the case study, which will be further addressed in the next section.

2.2 Case Study

As earlier discussed, there is little research on the application of takt time in HVLV manufacturing environments, hence building new theory is useful to gain new insights into the topic. Also, experience seems to be a primary driver in takt time implementation for HVLV manufacturers. Hence, a case study is relevant for this research as some of the strengths of this method, are building new theory and capturing actual practice and experiences (Eisenhardt, 1989, Voss et al., 2002). Yin (2014) defines a case study as;

> *An empirical inquiry that investigates a contemporary phenomenon (the "case") in depth and within its real-world context.*

Yin (2014) suggests five components for design of case study research:

1. **A case study's question:** This component concerns which *form* of the questions to ask related to the case study. For this research it was asked *how* takt time was implemented, and *why*, in order to answer the research questions.
2. **Its propositions:** The case study's questions relies on the propositions that takt time can be implemented in HVLV manufacturing environments, and that there are evidence that supports this implementation.
3. **Its units of analysis:** This component comprises how the "case" should be defined. For this research the case is defined as a manufacturer of HVLV products, which have implemented takt time based production. How the cases were selected will be further explained in section 2.2.1.
4. **The logic linking the data to the propositions:** This component relates to what data is relevant to support or contradict the propositions. Pattern matching techniques was used to identify patterns between the case and literature study, in terms of how and where takt time can be implemented for HVLV manufacturing. How the data was collected is presented in section 2.2.2.
5. **The criteria for interpreting the findings:** The data was interpreted if they were found to influence how takt time can implemented, how takt time can be determined, and if it supported or hindered the application of takt time.

2.2.1 Case Selection

This research contains a multiple-case study, where two HVLV manufacturers were chosen. These companies were chosen as they both are HVLV manufacturers that applies takt time in their manufacturing operations. The case companies are hereafter referred to as case companies A and B, and will be described in further detail in chapter 4. Case company A is a manufacturer of pressure vessels that uses three takt time based production lines for their assembly process. Takt time was implemented before this research commenced, unlike from case company B which takt time based production was under development during the course of this research. Case company B is a manufacturer of maritime equipment, and is implementing takt time in a sub-assembly line for their main equipment. The companies have some differences that is considered beneficial for the research as it can provide a broader perspective on the topic.

The case selection was limited by the scarcity of HVLV manufacturers that applies takt time, and the timeframe of the research. Voss et al. (2002) argue that fewer cases has the strength to provide depth in the research, but might be lacking in generalization purposes. In addition a weakness of building theory through case research is that it may result in narrow and idiosyncratic theory, which is difficult to generalize (Eisenhardt, 1989). When considering that the HVLV description of manufacturing environments can be broad, more cases could be beneficial to generalize the findings and increase its applicability.

2.2.2 Data Collection

Data from the case companies was collected using semi-structured interviews, observations at their facilities, attendance at meetings and collection of historical data concerning their products. In addition, informal conversations, especially during observations, were an important method to collect information and understand the context. The main objective of the data collection was to capture why and how takt time was implemented to support answers to research questions one and two. In addition, the historical data concerning their products was collected to test how analysing variability could be used to define a takt time, thus answering research question three.

Several interviews were conducted with key personnel from case company A. This includes the general manager, the production manager, chief of engineering, the production planner and the foremen. This was to capture the diversity of opinions and knowledge within the company in order to obtain a complete overview of the case. Interviews were done using both skype and phone, but most of the data were collected by staying at the company for ten days. This allowed for observations, in-depth investigations and discussions of findings as they occurred. A workshop was held in the end of the stay to discuss the findings, e.g. the framework for takt time system design (presented in section 5.1) and the variability analysis of the case company. This ensured the validity of the framework and the variability analysis from the case company’s perspective. In addition, company documents were obtained to understand their planning and manufacturing processes. Lastly, historical data concerning work content of their products were obtained in order to analyse the variability in their takt time system. These were obtained from their work hour log system and compiled in a spreadsheet for further analysis (see section 2.3).

Data collection from case company B was mostly related to the variability analysis. Production data concerning their products from a timeframe of 1.5 years were gathered in a spreadsheet for further analysis (see section 2.3). Correspondence through e-mail was done to validate the variability analysis so that it represented the way they had designed the takt time system. The company was visited to conduct observations in their production facilities in order to get an understanding of their operations, and how their takt time based production was designed. In addition, semi-structured interviews with the case company's production planner and production manager were done to discuss the variability analysis and validate the framework for takt time system design from the case company's perspective.

2.3 Variability Analysis

To answer research question three, a variability analysis was done for each company. The collected data concerned the manufacturing processes for products going through the companies' takt time systems and their processing times. The data from case company A concerned only thirteen pressure vessels as their annual volume is low and that they recently changed the data storage platform. Data from case company B concerned around 200 products. All the collected data concerned planned hours, as actuals hours were unobtainable due to inaccurate progress measurement. The data was categorized and separated in regard to which takt zone the work descriptions were assigned to.

In statistical process control, variation can be calculated using the range or the standard deviation (Chapman et al., 2017). The processing times for the vessels in each takt zone was analysed, and mean processing time and standard deviation was calculated. In addition, the number of products contained in each zone and minimum and maximum range of the processing times was identified. When all mean values and standard deviations for all the zones were calculated, the bottleneck operation was identified by calculating which zone that would most likely have the longest processing time. This was done using formula:

$$t_{USL,z} = \mu + \sigma$$

Equation 1: Calculation of upper specification limit for zone z

Where:

$t_{USL,z} = \ Upper\ specification\ limit\ of\ processing\ time\ for\ zone; z$

$\mu = Mean\ value\ of\ processing\ time$

$\sigma = Standard\ deviation\ for\ processing\ times$

The zone with the highest upper specification limit was identified as the bottleneck process of which the takt time could be calculated using the following formula:

$$Takt\ time = \mu_{bottleneck} + \alpha \cdot \sigma$$

Equation 2: Takt time calculation for bottleneck

Where:

$\mu_{bottleneck} = mean\ processing\ time\ for\ bottleneck\ takt\ zone$

$\alpha = quantile, fractile\ or\ critical\ value$

The α-value decides the width of the spread interval, in other words how large fraction of the population of samples is likely to complete within the takt time (Løvås, 2013, Chapman et al., 2017). Different values of α were tested, and the takt time was evaluated by counting the number of processes not completed within the takt time, and using column diagrams to observe how the different zones compared to the set takt time.

2.4 Analysis

Eisenhardt (1989) suggest two steps for analysis; analysis within case data, and searching for cross-case patterns. The first step concerns getting familiar with each case, to obtain a thorough understanding of the case and its uniqueness, which in turn facilitates for the cross-case analysis (Eisenhardt, 1989, Voss et al., 2002). This step was especially important concerning case company A, where a relatively long stay was emphasized, as they already had implemented the takt time system before the research commenced.

A great value of research is its ability to arrive at certain generalizations (Kothari, 2004), and searching for cross-case patterns is essential for generalization purposes (Voss et al., 2002). The findings from the literature study and the case study was compared in order to identify patterns. To answer research question 1, a framework developed by Buer et al. (2018), was used to compare characteristics from literature and the case studies. This was done to have a framework that facilitated comparison between the literature study and the case studies. This included for example characteristics of manufacturing environments and methods or approaches which facilitated for takt time. For research question two, approaches to how takt time control can be implemented, identified from the literature and case study, were examined to discover different concepts and aspects which needed attention in design processes. A tactic suggested by Eisenhardt (1989), is to select categories and search for similarities within the collected data. This was done by synthesizing the findings from the literature and case study in a conceptual framework.

According to Rallis (2018), a conceptual framework is an organizing structure that integrates ideas, facts, theory and perceptions related to the study in question. It provides focus and direction in a logical way in order to guide researchers in what they are exploring (Rallis, 2018). The framework was developed by identifying concepts from literature and the case study.

2.5 Validation

The chapter concerning the case study was sent to the case companies in order to validate the contents by assuring that the information was correct and that the important aspects were covered.

The framework was also validated with the help of the case companies, concerning how it compared to their situation and their opinion towards general implementation of takt time in HVLV. This was done multiple times during the iterative development of the framework and was done by using workshops and conversations over phone and e-mail.

3 Theoretical Background

This chapter provides the theoretical foundation of this research. The chapter is divided in three main parts. Section 3.1 will address HVLV manufacturing environments, which includes its main elements and characteristics. A framework is presented in section 3.1.3, which is used to describe HVLV manufacturing environments in general, as well as characterising different manufacturers throughout this report.

Section 3.2 will address the concept of takt time and explain how it can be determined. Further on, the section will introduce concepts that can be used when implementing takt time in HVLV manufacturing environments. Finally, four examples of takt time implementation in HVLV environments is presented.

Section 3.3 summarises this chapter, and provides the key outtakes in two tables; one for the concepts related to takt time implementation, and one for the characteristics of the examples discussed in the latter paragraph.

3.1 High-variety, Low-volume (HVLV)

The context of this research is confined to High-variety, low-volume manufacturing environments. Hence, it is necessary to discuss what HVLV is, and its characteristics.

HVLV manufacturing environments are related to the production of customizable products offered in a high variety and demanded in relative low volumes (Ricondo Iriondo et al., 2016, Jina et al., 1997). Together with an unstable demand, the manufacturing processes are often complex and subject to variation (Slomp et al., 2009). HVLV environments can be volatile, and can experience dramatic market changes; orders and shipments can change by more than 50% in volume (Adrodegari et al., 2015).

For HVLV organisations, order winning criteria are delivery performance, variety and customization (Jina et al., 1997, Birkie and Trucco, 2016, Hicks et al., 2000, Olhager, 2003, Willner et al., 2014). According to Hicks et al. (2000) delivery performance has two components; reducing lead times and increasing lead time reliability.

However, because of the high degree of customer and supplier involvement throughout the production phase, one can often find long lead-times, low customer satisfaction and poor resource planning (Jünge et al., 2016). The high levels of customisation also increases costs and risk (Hicks et al., 2000), and McGovern et al. (1999) argues that "*The challenge for ETO companies is to develop leaner, more cost effective supply chains*".

The actual characteristics of HVLV manufacturing environment has not reached consensus in literature, and there exists several possible combinations (Katic and Agarwal, 2018). Because of this, the following sections will address terms typically associated with HVLV manufacturing.

3.1.1 Engineer-to-Order and Make-to-Order

HVLV manufacturers typically apply Engineer-to-Order (ETO) or Make-to-Order (MTO) based on the level of customization offered to the customers and the manufacturing activities (Katic and Agarwal, 2018).

ETO and MTO are related to what is called the customer order decoupling point (CODP), or order penetration point (OPP), which can be defined as the point where customers are linked to products in a value chain (Olhager, 2003). Manufacturing environments are often distinguished into four main categories; make-to-stock (MTS), assemble-to-order (ATO), make-to-order (MTO) and (ETO). In one end we find the MTS where the CODP is typically placed in the inventory, while in the opposite end ETO is located with the CODP placed in the engineering or design phase (Willner et al., 2014).

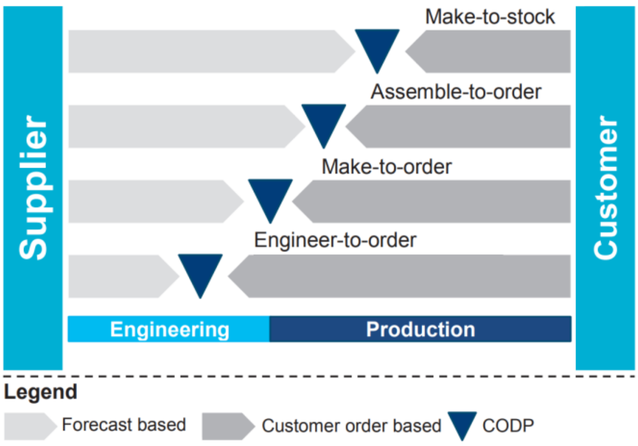

Figure 2: CODP, from (Willner et al., 2014)

ETO and MTO exhibits some similarities, and ETO can be characterized as a special case of MTO (Bäckstrand and Lennartsson, 2018). Willner et al. (2014) distinguishes between ETO and MTO by the level of customer specifications and involvement. With MTO customers selects design based on a pre-defined solution, while for ETO the design is entirely customer specific, thus ETO generally exhibits a higher level of customization than for MTO (Willner et al., 2014). In addition, the design phase in ETO can require several interactions with the customer throughout the manufacturing process, and the customer is more involved in ETO compared with MTO (see Figure 3). This difference in specification can be further specified by using three categories; pure customization, tailored customization and customized standardization, where the first applies to ETO and MTO encompasses the two latter categories (Hendry, 2010, Amaro et al., 1999).

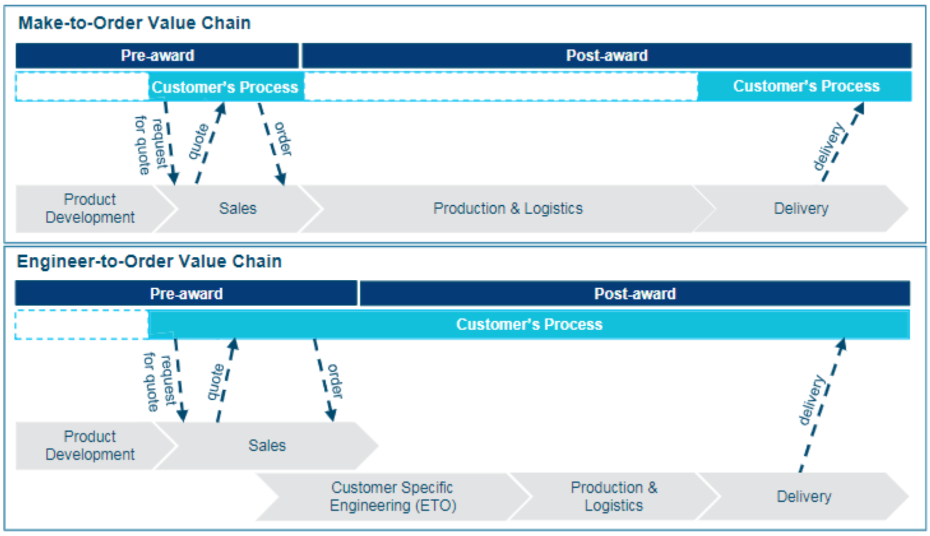

Figure 3: MTO vs. ETO, from (Willner et al., 2014)

3.1.2 Process Types

Manufacturing environments are often characterized by which manufacturing processing type that is applied (Porter et al., 1999). In principle, the essence of a manufacturing process is to convert inputs into outputs. According to Hill (2000), there are five generic types of manufacturing processes: *project*, *jobbing*, *batch*, *line* and *continuous processing*. Figure 4, adapted from (Hill, 2000), shows how the process types relates to product variety and production volume.

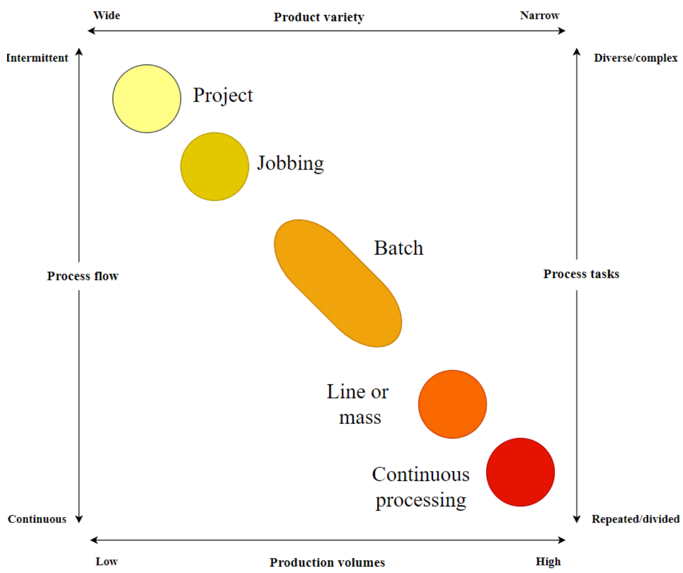

Figure 4: Processes related to volume and product range. Adapted from (Hill, 2000) and (Slack et al., 2007)

This indicates that HVLV manufacturing environments typically are located on the upper left. Project and jobbing are the main processes in HVLV (Slomp et al., 2009, Hendry, 2010, Rauch et al., 2015, Olhager, 2003), however HVLV manufacturer do often also include batch and flow processes (Alfnes et al., 2016, Hicks et al., 2001).

Project processes

Project manufacturing processing is typically large, complex, one-time projects for production on unique products (Chapman et al., 2017). The products are highly customised and in high varieties and low volumes, and is often built on the site of use, civil engineering or shipbuilding are industries that uses this kind of process (Hill, 2000, Porter et al., 1999, Kjersem et al., 2015, Slack et al., 2007).

Jobbing processes

Products involved in jobbing processing are customized to order requirement, and are produced in low volumes, often one-of-a-kind, and in wide varieties. This leads to variations in processes, routings and needed equipment for the different product varieties. This process type requires flexible highly skilled workers, and a flexible production facility, which is mainly referred to as a job shop. Here, the layout is organised into work stations or departments specified for a type of operation, often with dedicated equipment (Hyer and Wemmerlöv, 2002, Hill, 2000, Porter et al., 1999, Slack et al., 2007).

Batch processes

Batch processing refers to the production of products in small lots that require the same operations. The whole batch is typically completed for one operation before the subsequent operation is started. Batch processing can represent a wide variety of volumes, and has similarities with jobbing, although not the same degree of variety (Porter et al., 1999, Hill, 2000, Slack et al., 2007).

Line or mass processes

Line processing, or mass processes, exhibits higher volumes, and processes are often dedicated to the production of a single product or a small, specified range of products, as the same operations are required for every product. Lower levels of skill and labour intensity are typically required, compared to jobbing (Hill, 2000, Porter et al., 1999, Slack et al., 2007)

Continuous processes

In this process type, materials are processed into one or more products, going through successive stages designed to run continuously over longer periods of time. Product varieties are normally narrow, and volumes are high. Continuous processing do not require manual input, and worker tasks are mainly related to monitoring (Hill, 2000, Slack et al., 2007).

3.1.3 Characteristics of HVLV Manufacturing Environments

A framework for mapping planning environments, developed by Buer et al. (2018), is used to characterize HVLV manufacturing environments. These characteristics are presented in Table 2. This framework was selected as it can be used to map and compare the examples from literature and the case studies. In addition, the framework was tested on three ETO or MTO manufacturers. The framework contains 30 variables grouped into three categories; *Product*, *market* and *manufacturing process related.* These are widely used and are found critical for design of manufacturing planning and control systems (Olhager and Rudberg, 2002, Buer et al., 2018). All 30 variables are not used, and a selection of 12 have been selected, as the scope of this research does not include the entire planning environment, and focuses primarily on the physical processes (see section 1.4). In addition, Buer et al. (2018) also investigated the causality between the variables, and the selected variables have causalities to the level of customisation and product variety.

The selected variables are further explained as from Buer et al. (2018): *CODP placement* refers to the location in the value chain where the customer order is linked to the product. *Level of customization* represents the degree to which the customer can specify the attributes of the ordered product. *Product variety* refers to the quantity of product variants offered by the firm. *Bill-of-material (BOM) complexity* refers to the quantity of BOM levels of a typical product of a firm. *Demand type* describes the origin of production orders, ranging from forecasts to actual customer orders. *Volume/frequency* describes the annual manufacturing volume, and the product manufacturing frequency. *Frequency of customer demand* describes the demand regularity of a specific product. Unique means once between a period, and sporadic means several times within a period, but without a recognisable regularity. *Manufacturing mix* indicates the commonality of products, if they are considered homogeneous or mixed, from a manufacturing perspective. Homogeneous products require more or less the same manufacturing processes, while mixed products differs significantly. *Type of production* describes the average size and frequency of production runs. *Throughput time* represents the time it takes for a product to go through production. *Batch size* represents the typical size of a production order. *Frequency of production order repetition* describes how often production orders are repeated. *Fluctuations of capacity requirements* represents the level of variation in production capacity requirements. These fluctuations are mainly related to the changes in customer demand. *Material flow complexity* describes the material flow at the shop floor, and how the complexity is increased with number of possible routings and production layout.

Table 2: HVLV characteristics adapted from (Buer et al., 2018)

Variable	**Description**	**Reference**
Product related factors		
CODP	ETO or MTO	(Katic and Agarwal, 2018)
Level of customization	Fully customer specific, or some specifications are allowed.	(Jina et al., 1997, Buer et al., 2018, Adrodegari et al., 2015, Strandhagen et al., 2018, Birkie and Trucco, 2016, Hendry, 2010, Katic and Agarwal, 2018, Gosling and Naim, 2009, Willner et al., 2014, Stevenson et al., 2005)
Product variety	High	(Jina et al., 1997, Slomp et al., 2009, Ricondo Iriondo et al., 2016, Rauch et al., 2015, Katic and Agarwal, 2018, Stevenson et al., 2005)
BOM complexity	Medium to high. 3-5 levels or more.	(Jonsson and Mattsson, 2003, Bertrand and Muntslag, 1993, Amaro et al., 1999, Hicks et al., 2000)
Market related factors		
Demand type	Customer order allocation	(Buer et al., 2018, Slomp et al., 2009, Birkie and Trucco, 2016, Amaro et al., 1999)
Volume / frequency	Few large customer orders per year.	(Jina et al., 1997, Adrodegari et al., 2015, Slomp et al., 2009, Ricondo Iriondo et al., 2016)
Frequency of customer demand	Unique or block-wise/sporadic	(Buer et al., 2018, Bertrand and Muntslag, 1993)
Manufacturing process related factors		
Manufacturing mix	Varies between mixed and homogenous products, between and within organisations.	(Buer et al., 2018, Willner et al., 2014, Ricondo Iriondo et al., 2016, Vatne and Drevland, 2016)
Type of production	One-of-a-kind or small batch production	(Jonsson and Mattsson, 2003, Powell and van der Stoel, 2016, Ricondo Iriondo et al., 2016, Kjersem et al., 2015, Alfnes et al., 2016, Adrodegari et al., 2015)
Throughput-time	Varies a lot between manufacturers, and within organisations because of variations in cycle time. Throughput time typically increases from MTO to ETO.	(Buer et al., 2018, Jonsson and Mattsson, 2003, Lander and Liker, 2007, Rauch et al., 2015, Willner et al., 2016)
Batch size	Small or equal to customer order	(Jonsson and Mattsson, 2003, Willner et al., 2014)
Frequency of production order repetition	Non-repetitive production or infrequent production	(Bertrand and Muntslag, 1993, Powell and van der Stoel, 2016, Caron and Fiore, 1995, Stevenson et al., 2005)
Fluctuations of capacity requirements	Medium to high	(Bertrand and Muntslag, 1993, Rauch et al., 2015)
Material flow complexity	Medium to high	(Bertrand and Muntslag, 1993, Slomp et al., 2009, Wikner and Rudberg, 2005, Jina et al., 1997)

3.1.4 Turbulence in HVLV

As a consequence of the presence of a wide variety of customized products, unstable demand, variability and uncertainties are natural characteristics of HVLV manufacturing environments. Jina et al. (1997) uses the term “turbulence” to describe the experience of unpredictable and sub-optimal behaviours when generating outputs from inputs affected by variability and uncertainties. The authors identified four different types of turbulence (Jina et al., 1997, Alfnes et al., 2016):

1. Schedule: Changes in schedule because of variable demand
2. Product mix: Changes in product mix between periods because of marked differences. Can create variability in workload, depending on the differences in processing times for different products.
3. Volume: As with product mix, marked changes leads to changes in aggregated volumes.
4. Design: Level and frequency of design changes, which causes variability in engineering work and uncertainty in manufacturing.

Because of the low volumes, HVLV environments are especially prone to these types of turbulence, and the impact is more likely to occur because of the high variety (Jina et al., 1997, Powell and Pazos, 2010). According to Alfnes et al. (2016), HVLV manufacturer that exhibits some flow manufacturing processes can experience less turbulence. And as product characteristics have an impact on turbulence, designs with moderate complexity and innovation can reduce turbulence (Alfnes et al., 2016).

According to Bertrand and Muntslag (1993), HVLV environments may have to cope with three different uncertainties; (1) Product specifications, which involves product specific decisions concerning capacity lead time and price, (2) mix and volume uncertainty of the future demand, which makes demand forecasting difficult (3) process uncertainty, which makes capacity and resource planning difficult. They also argue that a firm is generally unaware of when orders are received, which also introduces uncertainty in planning.

As a consequence, the shop floor will experience variability in manufacturing. Changes in demand volume and distribution creates instable capacity requirements (Porter et al., 1999), and the variety of customized products creates variability in required processes, equipment, routings as well as causing variability in processing times and work content (Porter et al., 1999, Slomp et al., 2009, Katic and Agarwal, 2018, Alfnes et al., 2016)

3.2 Takt time

In this section, the fundamentals of takt time will be explained, before various concepts of how a takt time can be determined will be addressed. Finally, concepts that can be applied in implementation processes of takt time in HVLV manufacturing environments are presented.

Takt time is often defined as the rate of production that is synchronized with the rate of customer demand (Chapman et al., 2017), i.e. that the supply rate matches the demand rate (Frandson et al., 2013). "takt" is the German word for "beat", and it sets a rhythm for production. For example, a production line can be divided into zones, and a takt time is set for all the zones. In this way, products will move from zone to zone with every "beat", aiming to create continuous flow with little or no WIP inventory and less waste (Chapman et al., 2017). Takt time is linked to the continuous improvement spiral, as it aims to stabilize and create flow (Frandson et al., 2014, Chauhan et al., 2018). This forces problems surface, and these can be corrected to improve efficiency (Liker and Meier, 2006, Slomp et al., 2009).

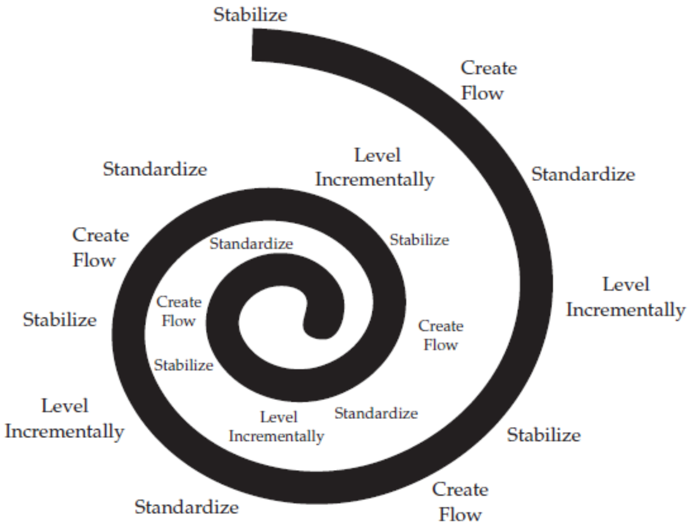

Figure 5: Continuous improvement spiral. From (Liker and Meier, 2006)

Takt time, processing time and cycle can easily be confused together, thus it is useful to distinguish them from each other. Processing time is the actual working time of a product on a station (Hopp and Spearman, 2001). Cycle time is the average time from a job is released in the beginning of a routing or a station until it finishes in the end of the routing or station (Hopp and Spearman, 2001). It can also be defined as the time it takes to do a set of operations before it is repeated (Duggan, 2013). Processing time is typically a component of cycle time together with for example setup time and move time (Hopp and Spearman, 2001).

Takt time sets the ideal production pace for customer demand, and a cycle time can be more or less than the takt time (Liker and Meier, 2006).

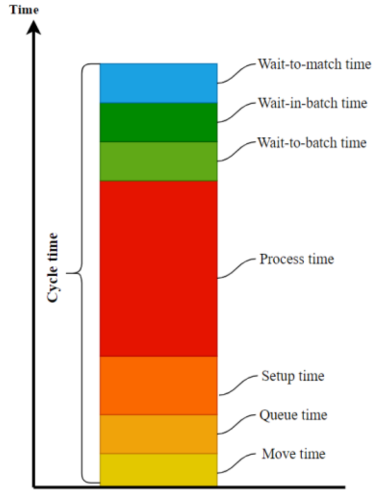

Figure 6: Cycle time components. Adapted from (Hopp and Spearman, 2001)

According to Liker and Meier (2006), takt time is a "reference point" to design work after, it can be used so see how cycle times relates to takt time – the ideal production pace, and identify bottlenecks and areas of improvement. Liker and Meier (2006) also argues that in the likely case of varying demand, a low takt time should be set in order to increase discrepancies in the production. In this way, more waste will be identified and potentially reduced to increase the efficiency.

An operation balance chart can be a useful visualisation tool to identify bottlenecks, to see which processes that will typically finish before or after the takt time, and to evaluate the capacity (Liker and Meier, 2006). An example is provided in Figure 7, where the dotted line represents a takt time, and the columns represent the cycle time for four different processes.

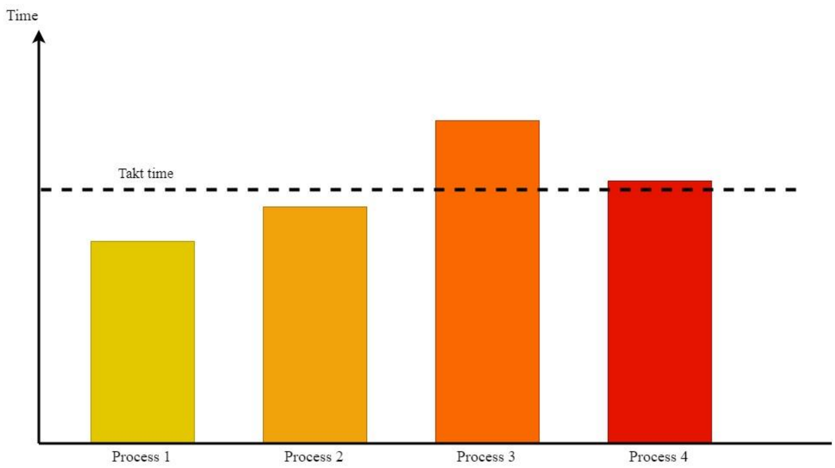

Figure 7: Example of operation balance chart

By studying this figure it becomes clear that process 3 is the bottleneck, and resources should be allocated to improve this process before the others. If the efficiency of process 3 is improved, the takt time can be set to what Liker and Meier (2006) calls the next “plateau” and the efficiency can be improved further. In the context of HVLV manufacturer, this means that takt time can facilitate lead-time improvement by continuously improving the bottleneck processes.

However, a continuous improvement culture is not necessarily easy to achieve. According to Powell and van der Stoel (2016), the mentality that “we’re different” makes it challenging to create a common understanding among employees. To succeed with takt time, it is important that everyone is on board with it (Vatne and Drevland, 2016), and that there is a clear communication and thorough planning (Frandson et al., 2013). Slomp et al. (2009) found that after some months after implementation of takt time, orders where late due to that the workers where deviating from the planned sequence. Reasons for this could be problems such as machine break downs, but they argue that the workers should follow the principles of lean production and focus on problem solving, even though they wanted to continue producing. Frandson et al. (2013) found that takt time required a high degree of discipline and order to hold the plan, and that this level of detail could cause stress for those responsible for coordinating work.

3.2.1 Defining Takt Time

Takt time can be formulated as follows, according to Duggan (2013):

$$\frac{Effective\ working\ time}{Sum(Demand\ during\ period)} = Takt\ time$$

Equation 3: Takt time calculation

The demand for a product family can be calculated using forecasts or historical sales data for a given period (Duggan, 2013, Ricondo Iriondo et al., 2016), or using a backlog of orders (Slomp et al., 2009). Takt time, in its common context, is normally defined in terms of seconds or minutes, while for HVLV manufacturing environments the takt time can be defined in hours, days or weeks (Ricondo Iriondo et al., 2016, Binninger et al., 2017).

Takt time is traditionally used in repetitive manufacturing environments, such as in MTS. The definition of takt time, as presented above, depends on a consistent demand, hence takt time will vary when demand varies (Powell and van der Stoel, 2016). Hence, if takt time calculation is based on a demand or backlog, it is likely to fluctuate along with demand, which is unfortunate for standardisation (Liker and Meier, 2006). In repetitive manufacturing, takt time is typically calculated based on the demand and available capacity as in Equation 3. However, in non-repetitive environments takt times can be defined differently. If the time frame is confirmed, it can be matched to the available resources, or the bottleneck trade could be maximized and then other trades would be aligned to it (Frandson et al., 2013). Takt time can also be chosen based on trial and error (Tommelein, 2017).

Takt rate

As an alternative to takt time, Lander and Liker (2007) proposes using *takt rate*, which is the amount of parts produced per day that is needed to meet the demand. They investigated the use of takt time at a manufacturer of low volume, highly customised clay tiles. Because of demand variability and consequently variability in process cycle time, a takt time would be average and less meaningful for daily production. Alfnes et al. (2016) suggest that in the case of high turbulence, takt rate defined as pcs/day or pcs/week could be used as an alternative to takt time.

Takt capability and takt mode

Duggan (2013) suggest another approach to takt time in the case of variable or unknown customer demand; takt capability. Takt capability is a measure of how much a manufacturer is able to produce per period. With this approach, one has to consider both mix and volume as components in defining a takt capability, as setup times would affect the lead-time with wider product mixes (Duggan, 2013).

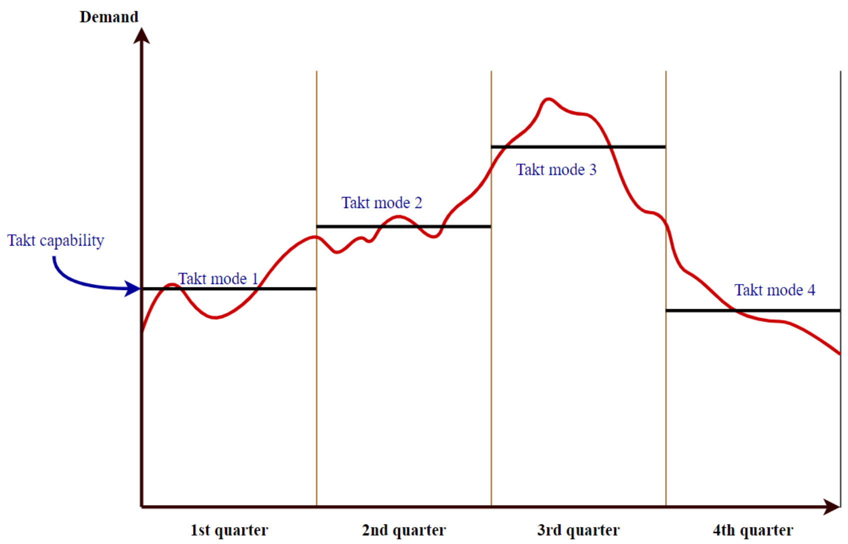

Figure 8: Takt modes based on seasonal demand. Adapted from (Duggan, 2013)

To cope with demand fluctuations Duggan (2013) also suggests that several takt capabilities can be created in order to answer demand fluctuations or seasonal demand (Alfnes et al., 2016). This is referred to as *takt modes,* which are pre-defined takt capabilities that are set for a certain demand situation – for example for every quarter of a year as can be observed in Figure 8.

3.2.2 Concepts for Takt Time Based Production Control in HVLV

This section aims to cover some aspects of how to approach the implementation of takt time control. In addition, managing variability is key to achieve stability (Liker and Meier, 2006), thus various approaches to how this can be done in relation to takt time is useful when investigating implementation of takt time.

Takt time implementation in construction

The determination of takt time in construction is based on the bottleneck task or the project requirements (Seppänen, 2014). Tommelein (2017) suggests a method for takt time planning of non-repetitive work. It contains five steps in an iterative cycle, which illustrates *how* takt time can be applied to a project (see Figure 9). These steps are further explained here based on (Tommelein, 2017, Frandson et al., 2013):

1. Collect data: This step involves identifying what work needs to be done, and where. Frandson et al. (2013) suggests that those who understand the details of the work, such as foremen, are included in this process.
2. Define zones and takt time: Zones are where workers are controlled to, and they are defined based on the information collected in step 1. Ideally, zones should be defined so that they contain equal batches of work. The takt time can be chosen based on trial and error. However, it should be set so that the workers can have some time left after the work is completed, as this time serves as a buffer.
3. Create flow and balance the system: This step involves identifying sequences, i.e. who has to work in a zone before or after whom. This facilitates for balancing the flow by identifying the speed of the different trades.
4. Pull plan to reach team agreement: This step concerns explaining the preliminary plan with the different teams to reveal concerns and possibilities. This helps validating the feasibility of the plan and to take corrective action.
5. Fine tune the system: Trades can add to what work that can be done outside the takt zones, for example on a backlog to fill buffer times.

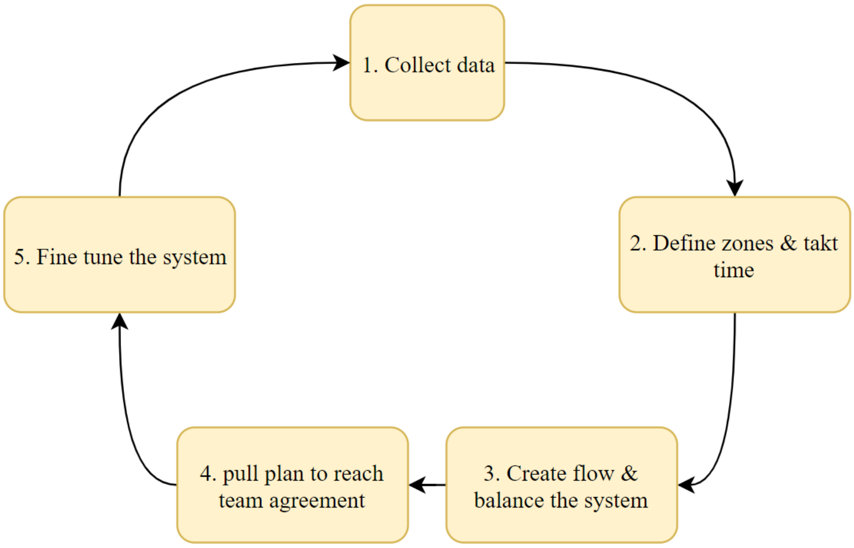

Figure 9: Process steps for takt time planning. Adapted from (Tommelein, 2017)

Construction differs from some types manufacturing, as the takt time plan is specified for a project, where the due dates and work to be done is more or less known. According to (Tommelein, 2017), takt time planning in construction seeks to define spaces in a facility where each trade can get their work done in a reliable manner according to the planned sequence and takt time. Thus, this approach is perhaps applicable for larger project processes, such as shipbuilding (Heinonen and Seppänen, 2016).

Moving products vs. moving workers

Creating flow is key to eliminate waste (Lander and Liker, 2007), but achieving flow of products is not always feasible. Not all products are easily movable and cannot be produced in moving, takt time controlled assembly lines. This is typical for project processes (Porter et al., 1999). An alternative to move the products is to move the workers in a takt time controlled pace. This is the approach used in construction, where the different trades move around in the facility (product) that they are constructing (Tommelein, 2017).

This approach was also applied by Ricondo Iriondo et al. (2016) (see example 2 in section 3.2.4), who discarded moving the machines, even though it was preferable to have a paced production system. This was due to the machines' technical complexity, variety, large dimensions and large investments in infrastructure to facilitate the actual transportation of the machines. Instead of assigning operations to takt zones, people are allocated to operations which are grouped into stages. In this way, the products would remain stationary and working teams with a specified set of tasks and tools would move around to the different products in a takt controlled pace (Ricondo Iriondo et al., 2016).

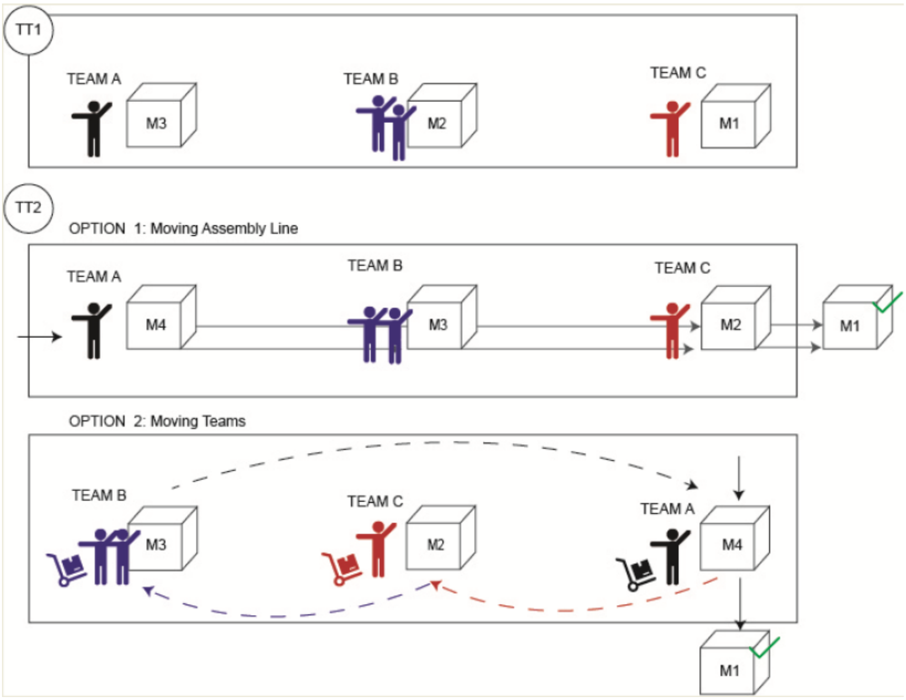

Figure 10: Moving products vs. moving workers. From (Ricondo Iriondo et al., 2016)

Ricondo Iriondo et al. (2016) implemented the takt time with the moving takt time using a standard work balancing technique with the following steps:

1. Calculation of takt time
2. Breakdown of machine assembly work
3. Calculation of average operation time
4. Grouping of operations in stages
5. Allocation of people to operations

Product families

Because of customized products, and varieties in product mixes the processing times also varies between products (Slomp et al., 2009). Figure 11 shows how it can look if maximum and minimum cycle times are included in addition to the average cycle time for each process. This further complicates the implementation of takt time, as the deviations between cycle times and takt time will fluctuate.

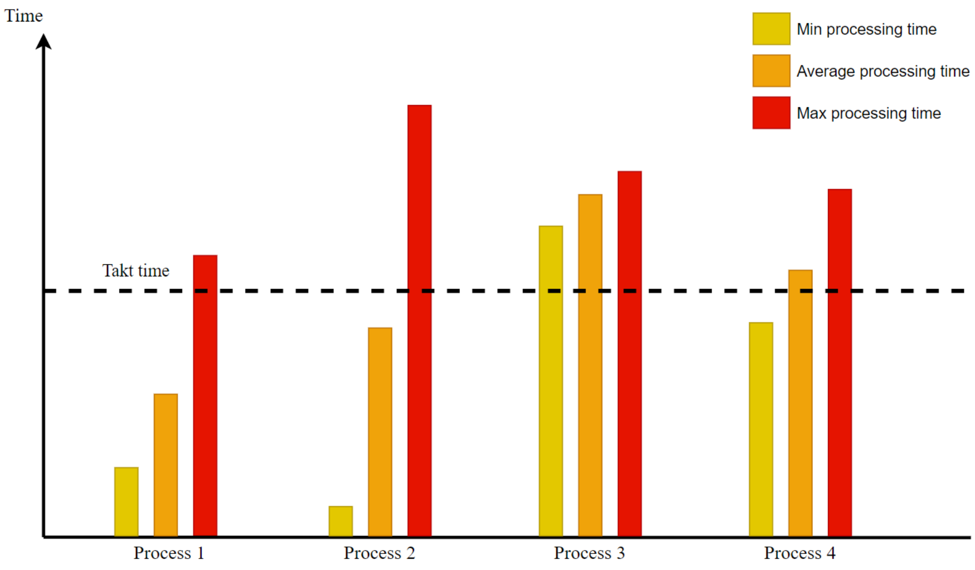

Figure 11: Operation balance chart with variable processing times

Takt time is not necessarily applicable to all product families, as the variability can be too large. Duggan (2013) suggests that products should be grouped so that the variability in work content within a family is less than 30%. Ricondo Iriondo et al. (2016) found that a separate area for project based assembly of the most customized products was necessary. Similarly, Vatne and Drevland (2016) found that the ground floor of a construction project was too non-repetitive that it was excluded from the plan. Instead, it was set as a task buffer for available workers.

Reducing variability is crucial to obtain stability, and doing that in HVLV is challenging as balancing people, materials and machines is almost impossible (Liker and Meier, 2006). Liker and Meier (2006) continues to suggest that if variability is uncontrollable, isolating it is the best alternative, for example by dividing products into families of similar characteristics.

Hyer and Wemmerlöv (2002) suggests nine approaches of how to define product families:

1. **Product type:** Group products of the same type or function into families.
2. **Market:** Group all products sold in a certain geographical market in one family.
3. **Customers:** Group all products sold to one or more customers in the same family.
4. **Degree of customer contact:** Group products according to the degree of influence the customer has on the final product.
5. **Volume range:** Group products with similar volume ranges into the same families.
6. **Order stream:** Group products with similar customer order patterns in same families.

7. **Competitive basis:** Allocate all products that compete on the same basis to the same families.
8. **Process type:** Group products or parts requiring similar processes in the same families.
9. **Product characteristics:** Group products with same physical features or raw material into families.

Determining product families is challenging in HVLV environments, as similarities between products might be scarce (Alfnes et al., 2016). However, the examples of takt time implementation, explained in section 3.2.4, suggests that grouping products by process type is possible as all of the examples had some degree of homogeneous product mix. In addition, to cope with the variability in processing time, as earlier discussed in this section, products can be grouped in regard to similar processing times (Liker and Meier, 2006).

An option that could facilitate for product family creation is prefabrication. In the case of example 3 discussed earlier, the takt based manufacturing involved units that was prefabricated before it was assembled (Kjersem et al., 2015). In this way the product family in the takt based assembly was more homogeneous compared if the entire assembly was included. In a multiple case study of prefabrication and takt time, Chauhan et al. (2018) found that the two concepts benefitted from each other, as the variability in the takt time controlled production is reduced and that material flow in the prefabrication is coordinated by the takt time.

Production levelling

Production levelling (often referred to as Heijunka in terms of Toyota terminology, or production smoothing) is a concept that aims to distribute jobs into a production line so that the workload can be balanced, and to avoid fluctuations in capacity requirements (Birkmann and Deuse, 2007, Chapman et al., 2017). Variability in demand and workload can potentially cause overloading or under-utilization of the production capacity, which is especially true for HVLV manufacturers (Hüttmeir et al., 2009). Thus, achieving a levelled production is desirable for any manufacturer (Hopp and Spearman, 2001), but it can be challenging for HVLV manufacturers.

Production levelling relies on relatively stable and predictable demand, and in order to protect the production from demand volatility it requires a certain finished goods inventory. (Hüttmeir et al., 2009, Birkmann and Deuse, 2007). For some manufacturers, e.g. those using

MTS strategy, they can do this by decoupling the internal supply chain from the external, but HVLV manufacturers cannot easily implement this decoupling by nature (Jina et al., 1997). Hüttmeir et al. (2009) argues that there is a trade-off between leanness and responsiveness, and if demand volatility is strategic, production levelling should be relaxed or eliminated. This indicates that HVLV manufacturers might lose competitiveness by levelling production, as they become less responsive.

However, achieving some production levelling can be achieved by decoupling sub-assemblies from final assembly (Jina et al., 1997). If the sub-assembly is not on the critical path of the production, output buffers can be used to dampen the variability and smooth the production instead of assembling so that the products are finished when they are needed.

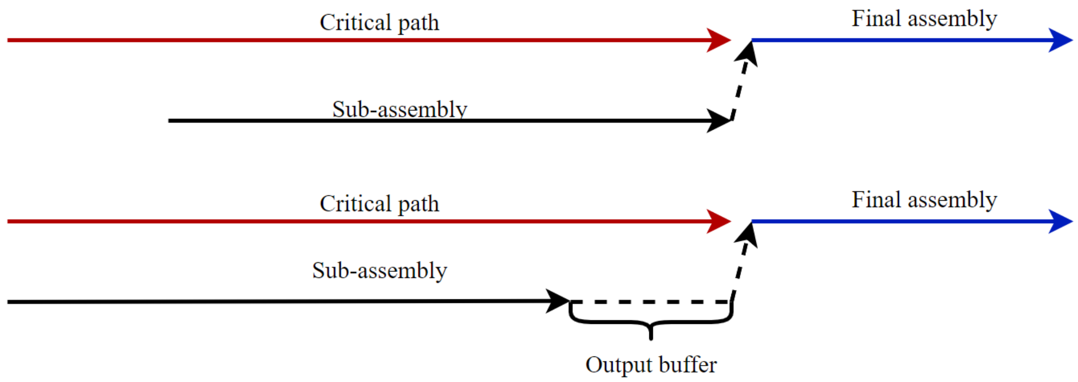

Figure 12: Production levelling of sub-assembly

Takt time grouping

Related to product families is the method takt time grouping (TTG), developed by Millstein and Martinich (2014). In this method, products are grouped together into takt time groups of similar time buckets, and the takt time is calculated as time per group instead of time per unit. The groups have different compositions depending on the cycle times of the inhibited products. Products with longer cycle times will have smaller TTG quantities, opposite to products with shorter cycle times. Products of similar type are grouped together in order to minimize set-up time.

The motivation behind the method was that high variability in cycle time and work content, moving constraints, and long setup-times was found problematic for a mid-sized manufacturer. These issues are similar to what HVLV manufacturers experience, but the manufacturer had relatively high volumes and throughput rates compared to HVLV manufacturing. By implementing TTG Millstein and Martinich (2014) found that the throughput rate increased, a more stable flow and better machine utilization was achieved.

Generalized takt time

Slomp et al. (2009) suggests that takt time can be applied as "generalized takt time control", meaning that takt times are set for a system of workstations rather than for each workstation, as routings can be product specific. In a multi-project environment, this approach can handle some variation in the case of a mixed manufacturing mix. This approach also gives workers the incentive to work on the right order at the right time (Slomp et al., 2009).

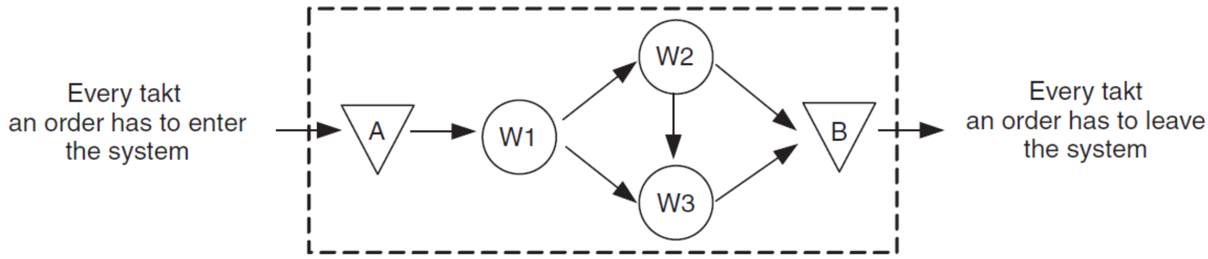

Figure 13: Generalized Takt time control. From (Slomp et al., 2009)

Buffers

According to Hopp and Spearman (2001), there are three types of buffers that are used to deal with variability in production systems. 1) Inventory, 2) capacity and 3) time. Buffers can also be used to improve performance related to takt time control.

As CODP are located far upstream for HVLV manufacturing environments, inventory buffers are less useful (Powell and van der Stoel, 2016). However it is difficult to avoid capacity loss because of the variability in work content (Linnik et al., 2013), thus having a workable backlog done "off takt", might be useful. Vatne and Drevland (2016) found that a having some work to be done off-takt was a useful task buffer to deal with workers waiting on work in the takt time plan, which corresponds to the fifth step in the method for takt time implementation in construction (Tommelein, 2017). Faloughi et al. (2015), differentiates between two kinds of WIP, namely "work waiting on workers", and "workers waiting on work". They argue that it is difficult to minimize both simultaneously, but that workers waiting on work should be minimized, as keeping workers busy tends to maximise throughput (Hopp and Spearman, 2001). Slomp et al. (2009) found that maintaining a certain amount of WIP was crucial to deal with the variability in routings and processing time, and if a flexible workforce is maintained, excess capacity caused by variability in the takt time based production can be used to work on a backlog or work done without takt time, such as with Ricondo Iriondo et al. (2016), which had a project based assembly area for the products of higher levels of variability.

For HVLV manufacturers, required capacity can be challenging to define, as it depends on the product mix at any time, and that process times can vary (Porter et al., 1999, Slomp et al., 2009). Capacity can be used as a buffer in order to cope with variability in processing times, so that build-up of WIP is avoided when work content increase. In step 2 in the method for takt time implementation in construction, Tommelein (2017) suggests that a capacity buffer should be added to the takt time so that workers have some time left to deal with unforeseen issues. In this case it is useful to have a flexible, cross-trained workforce so that capacity can be utilized where it is needed most (Slomp et al., 2009, Hopp and Spearman, 2001). Having capacity buffers might lead to wasted capacity (Hopp and Spearman, 2001), as discussed in the latter paragraph.

In their approach to implement takt time, Ricondo Iriondo et al. (2016) used time as a buffer to deal with variability. They applied basic statistics, and calculated mean values together variability values (range) to calculate the takt time. In this way, jobs that exceed the average processing time might still complete within the takt time. However, time buffers comes at the expense of longer lead times or inflated cycle times (Hopp and Spearman, 2001), which contradicts the purpose of takt time to reduce lead time.

Last Planner® System and Lean Project Planning

In lean construction, takt time is often used together with the Last Planner® System (LPS). This production control system compliments takt time, by increasing plan reliability, facilitates for continuous improvement, and engages the foremen in planning (Frandson et al., 2014, Jünge et al., 2015) – which can be related to step 1 in the method for takt time implementation in construction (Tommelein, 2017)

LPS was created in the 90's as a system of production control for production management (Ballard and Tommelein, 2016). During planning, more and more information is obtained as the plan unfolds, hence more detailed planning leads to more incorrect plans (Frandson et al., 2014). By decomposing planning into certain processes with different level of detail, LPS can improve plan reliability (Ballard, 2000).

The Master Scheduling and Phase Scheduling identifies what **should** be done, when and by whom (Ballard and Tommelein, 2016). The Look-ahead Planning identifies what work **can** be done, by using constraints for activities (Frandson et al., 2014). Koskela (2000) provides seven preconditions which must be met for a task to be executable; (1) design (information

(Emblemsvåg, 2014b)), (2) components and materials, (3) workers, (4) equipment, (5) space, (6) connecting work and (7) external conditions (weather, laws etc.).

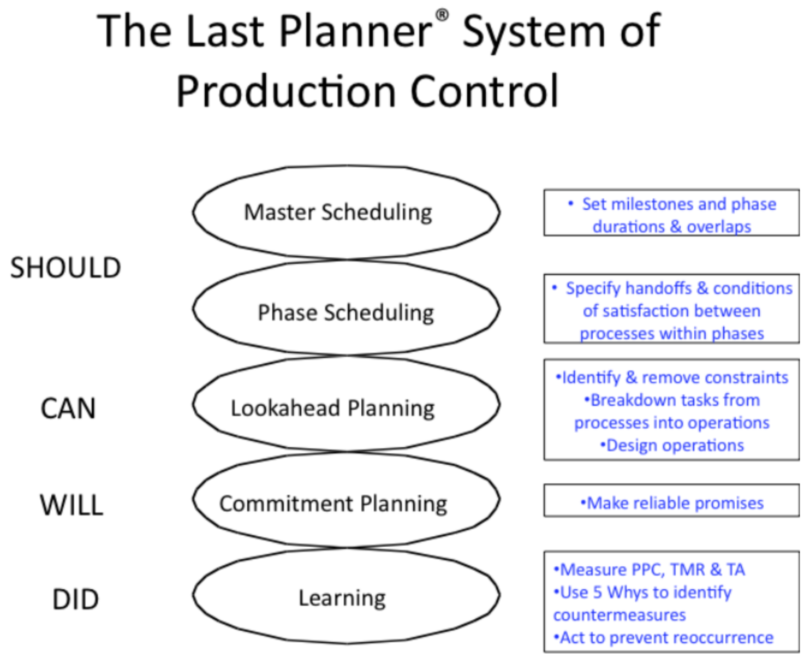

Figure 14: Should – Can – Will – Did (Ballard and Tommelein, 2016)

Commitment plans are made from executable tasks, where what **will** be done is committed to by the Last Planner. From here the production control commences (Emblemsvåg, 2014b). Percent Planned Complete (PPC) measures the percent of activities completed as planned (Jünge et al., 2016), and it is used to measure reliability, and it will rise when commitments are only made for executable tasks (Ballard and Tommelein, 2016). Finally, by comparing **did** to **will**, deviations can be identified and analysed to learn and prevent reoccurrence. Techniques such as 5 Whys can identify root causes and countermeasures, while Plan-Do-Check-Act (PDCA) can be used to test the effects of the countermeasures (Ballard and Tommelein, 2016). Figure 15 shows how the different levels of planning are connected.

Emblemsvåg (2014b) argues that LPS cannot handle advanced engineering design work, and introduces Lean Project Planning – a combination of Earned Value Management (EVM) and LPS. EVM provides project performance measurement by comparing actual schedule performance and expenses with a baseline, which is generated by schedules and budgets from the project plan development (Kendrick, 2014). EVM can be used to assess budget and schedule performance by using the metrics Cost Performance Index (CPI) and Schedule Performance Index (SPI), respectively. By combining LPS and EVM, physical progress measurement is enhanced and the project performance measurement reliability is improved (Emblemsvåg, 2014a).

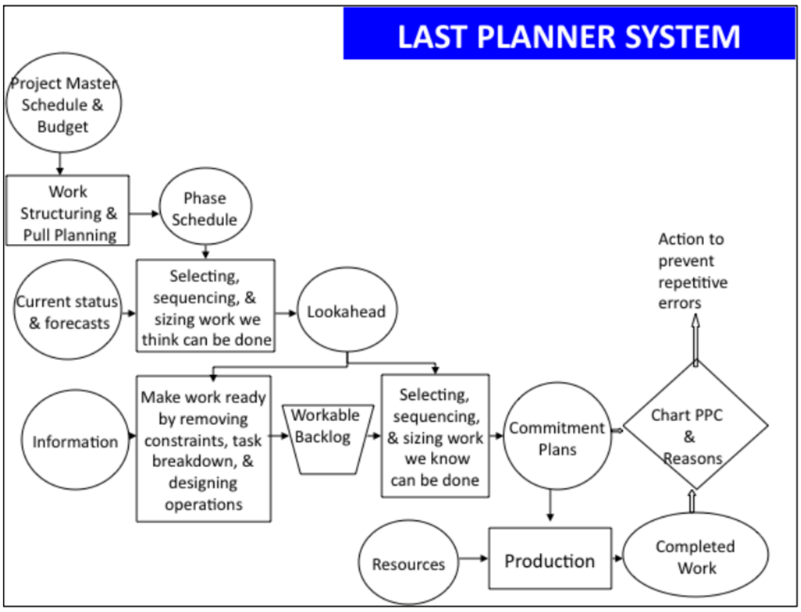

Figure 15: Last Planner® System,(Ballard and Tommelein, 2016)

3.2.3 Other Lean Concepts

According to Slomp et al. (2009), suggests that takt time control is one of three elements of lean production in MTO, together with constant-work-in-progress (CONWIP) and First-in-first-out (FIFO) sequence. These elements are closely connected to the pull principle, which is interlinked with flow (Liker and Meier, 2006, Hopp and Spearman, 2004, Kjersem et al., 2015). Hence, it is useful to explain pull, CONWIP and FIFO here.

The concept of pull is to produce only what is demanded, and when it is demanded by the customer (Chapman et al., 2017). In this way one could argue that HVLV manufacturers operate with pull systems, as production commences after a customer order is received. But this has to be referred to as *demand pull* and not to be confused with *production pull.* Hopp and Spearman (2004) uses the following definition of pull and distinguishes it from push:

> *A pull production system is one that explicitly limits the amount of work in process that can be in the system. By default, this implies that a push production system is one that has no explicit limit on the amount of work in process that can be in the system.*

The amount of work in process can be controlled by CONWIP which is a generalized form for Kanban, based on a card signalling principle (Kjersem et al., 2015). While Kanban is product specific, CONWIP is used to control entire production lines, by defining a maximum amount of work in progress (WIP), and is therefore a pull system (Hopp and Spearman, 2004, Powell and van der Stoel, 2016). In a CONWIP system, an order can only be released if an available card can be attached to it. The number of cards is limited and predefined, so if there are no cards available a product has to leave the system before a new one can enter (Slomp et al., 2009, Chapman et al., 2017)

A FIFO sequence means that products should be processed in the order that they arrive, so that the first order that comes to the system, is the first to leave (Hopp and Spearman, 2001, Chapman et al., 2017). Slomp et al. (2009) found that FIFO together with CONWIP and takt time control, forced workers to focus on the oldest orders, hence stimulating them to work on the "right" orders.

3.2.4 Examples of Takt Time Implementation

This section contains a study of four different examples from literature, which comprises the implementation of takt time in different HVLV environments. Each example is briefly introduced before their characteristics are presented in Table 4 in the summary chapter 3.3, based on the same framework as discussed in section 3.1.3.

Example 1, (Slomp et al., 2009, Bokhorst and Slomp, 2010): Two articles discusses the same case study from an internal supplier to a manufacturer of electrical power distribution and control equipment for industrial, commercial and residual markets. Takt time, together with CONWIP and FIFO were implemented at the production unit of components and semi-manufactured products from cobber bars. The production was considered to be a typical MTO job shop with low volumes, small lot sizes and a variety in part types and routings. The implementation yielded reduction in flow time and improvement of service level and delivery performance from 55% to 80%.

Example 2, (Ricondo Iriondo et al., 2016): Single case study of a Spanish manufacturer of centreless grinding machines. The manufacturer offered 3 machine models with 6 sub-models, however every single machine was customized. The manufacturing environment was classified as mixed MTO and ETO. Takt time was implemented for a part of the assembly, and the products with higher levels of customization and variability was left outside the takt time based assembly.

The findings showed that takt time could be implemented to a significant part of the manufacturing process. Better efficiency was achieved with takt time compared to the traditional approach, lead time reliability increased from 60% to 75%, productivity was improved and management was simplified as the production manager reduced time spent on scheduling. Another interesting benefit, was that the workforce shifted from task orientation to goal orientation which introduced a continuous improvement culture. This was because to manage variability, the workforce was cross-trained at different stages and operations, so that they could vary the workforce depending on the required work. This led to empowerment of the workforce, enhanced the collaboration and promoted viewing the process as a whole.

Example 3, (Kjersem et al., 2015): Action research of implementation of Kanban, CONWIP and takt time at a shipbuilder's assembly line of hulls. The shipbuilder builds complex and highly customised offshore vessels, mainly for the offshore oil and gas industry. The manufacturing environment was ETO.

The implementation of Kanban, CONWIP and takt time yielded improved material flow and reduced lead time, takt time especially improved predictability of lead times. In addition, planning and scheduling was improved as the number of units in the line were limited and worker allocation was better controlled.

Example 4, lean construction: This covers not only one, but several examples of takt time implementation in the construction industry. Several empirical studies has been done on the implementation of takt time in the construction industry. In construction, the facility is the "product", and contrary to manufacturing is always stationary and dictates the layout in which the work must be done (Tommelein, 2017). The construction of a facility is subject to variation, as different trades require various amounts of work, which can differ from room to room, or floor to floor (Linnik et al., 2013).

Literature from lean construction suggests several benefits from implementing takt time. Applying takt time should reduce the overall project duration (Seppänen, 2014). Several case studies has proven this benefit, some even find that the completion time is more or less halved (Frandson and Tommelein, 2016, Yassine et al., 2014), or reduced as much as 73% (Heinonen and Seppänen, 2016). Takt plans can identify problems, as incompletion of activities within takt indicates problems which can be dealt with early. Vatne and Drevland (2016) suggests that other traditional approaches might not indicate problems before it is too late. Chauhan et al. (2018) also found that the use of standard durations in the takt plan simplified and visualised the schedule which enabled a deeper understanding of the project. In addition, takt time is an enabler to reduce work-in-progress, for example Heinonen and Seppänen (2016) found an reduction in WIP by 99% for in their case study.

3.3 Summary

This section summarises the theoretical background in two sub-sections. Section 3.3.1 covers the concepts related to takt time implementation in HVLV manufacturing environments, while 3.3.2 addresses the characteristics of the four examples of takt time implementations, which was introduced in sub-section 3.2.4.

3.3.1 Concepts Related to Takt Time Implementation in HVLV Manufacturing Environments

The concepts related to takt time implementation are exhibited in Table 3.

Table 3: Summary of concepts identified from literature, related to the implementation of takt time in HVLV

Concept	**Comment**
Takt time determination	Set takt time low to increase discrepancies and stimulate improvement (Liker and Meier, 2006). Calculate takt time by dividing effective working time by demand from backlog (Slomp et al., 2009). Calculate takt time based on statistics from historical data (Ricondo Iriondo et al., 2016). Takt time varies along with demand (Powell and van der Stoel, 2016), which is unfortunate for standardization (Liker and Meier, 2006). Set takt time based on bottleneck, and align other operations to it (Frandson et al., 2013, Tommelein, 2017, Seppänen, 2014).
Takt rate	Use takt rate as psc/day or psc/week, as variability in demand and processing time makes takt time less useful (Lander and Liker, 2007, Alfnes et al., 2016).
Takt capability	In the case of variable or unknown demand, define takt time as the production capability, i.e. how much a manufacturer is able to produce (Duggan, 2013).
Takt mode	Define sets of takt modes (predefined takt capabilities) to respond to demand fluctuations or seasonal demand (Duggan, 2013, Alfnes et al., 2016).
Approach to takt time	Collect data by involving those who understand the details of the work (foremen) (Frandson et al., 2013). The process of determining a takt time is iterative (Tommelein, 2017).
Moving takt teams	If products cannot be moved, group operations into stages and allocate to worker teams which move according to takt time (Ricondo Iriondo et al., 2016).
Product family	Isolate variability by defining product families, e.g. by process type (Liker and Meier, 2006, Hyer and Wemmerlöv, 2002). Group products so that the variability in work content is less than 30% (Duggan, 2013). Exclude products/process with high variability from takt time controlled production (Ricondo Iriondo et al., 2016, Vatne and Drevland, 2016). Prefabricate components to reduce product complexity (Kjersem et al., 2015, Chauhan et al., 2018), and facilitate for product family definition.
Production levelling	Decouple subassemblies and use output buffers to allow for production levelling to dampen impact from variability (Jina et al., 1997).

Takt time grouping	Group products into takt time groups of similar time buckets to balance the line in the case of cycle time variability (Millstein and Martinich, 2014).
Generalized takt time	In case of routing variability, set takt time to system of workstations rather than to individual workstations (Slomp et al., 2009).
WIP buffers	Maintain a certain amount of WIP or backlog as a buffer to avoid capacity loss (Tommelein, 2017, Slomp et al., 2009, Linnik et al., 2013). Minimize "workers waiting on work" (Faloughi et al., 2015), to keep workers busy (Hopp and Spearman, 2001).
Capacity buffers	Use capacity buffers to cope with variability in processing times to avoid WIP build-up (Tommelein, 2017).
Time buffer	Integrate time as safety buffer in takt time calculation to avoid discrepancies (Ricondo Iriondo et al., 2016).
LPS/LPP	Use Last Planner® System or Lean Project Planning to increase reliability (seven conditions) and facilitate for continuous improvement (Frandson et al., 2014, Ballard, 2000)

3.3.2 Characteristics of Examples of Takt Time Implementation

This section contains the characteristics of the examples earlier introduced in section 3.2.4, by using the framework introduced in section 3.1.3.

The references related to the four examples do not fully address how the characteristics relates to the variables used in the framework. Hence, some guesswork and other references with comprises manufacturing environments with similar conditions is used to further characterise the examples. Guesswork is indicated with cursive text, and other references is referred to in the explanation. Some variables are left un-answered, because of lack of information. In this table, a new variable is added in addition to those provided by Buer et al. (2018); *takt time*, which refers to the takt time used in the examples.

Table 4: Characteristics of examples of takt time implementation, from literature

Variable	**Example 1: (Slomp et al., 2009, Bokhorst and Slomp, 2010)**	**Example 2: (Ricondo Iriondo et al., 2016)**	**Example 3: (Kjersem et al., 2015)**	**Example 4: Lean construction**
Product related factors				
CODP placement	MTO	ETO/MTO	ETO	ETO/MTO
Level of customization	A large proportion of the products are highly customized.	High customization level. Three models with six sub-models were offered in the case. All machines were customized.	Fully customer specific.	High customization level (Frandson et al., 2014).

Product variety	High	High	High	Level of variety varies from project from project (Linnik et al., 2013).
BOM complexity	*Low. 1-2 levels and several items.*	High. More than 5 levels (Saiz et al., 2013).	Low	
Market related factors				
Demand type	*Customer order allocation*	Customer order allocation	Customer order allocation.	Customer order allocation
Volume / frequency	Low volumes. Frequency is not indicated in the articles.	*Few large customer orders per year.* (The case was multi-project environment and long lead-times.)	Few large customer orders per year.	Volume is more or less specified to the project.
Frequency of customer demand	*Block-wise/sporadic*	*Unique*	Unique	Demand is more or less known, and the project is specified to a fixed amount of time (Frandson et al., 2014).
Manufacturing process related factors				
Manu-facturing mix	Varies between mixed and homogenous products. There is a great variety in routings, however a dominant flow is present.	Varies between homogeneous and mixed products. The assembly was divided into two stages were the first consisted of similar processes, hence homogeneous products. The second had more complex processes.	Homogeneous. Takt time was implemented for the assembly unit, which consisted of similar processes for every product.	Varies between mixed and homogeneous. Vatne and Drevland (2016) found that the ground floor contained too much variability in processes, compared to the other floors, in order to be included in the takt time plan.
Type of production	Small batch production	One-of-a-kind	One-of-a-kind	*One-of-a-kind*
Throughput time	Days. It was improved from 4.2 days to 1 day after the implementation of CONWIP/FIFO/takt time	Days. Assembly took between 480 and 520 hours.	Weeks.	Weeks or months.
Batch size	Small or equal to customer order	Equal to customer order	Equal to customer order.	*Equal to customer order*
Frequency of production order repetition	In-frequent production	Varies between non-repetitive and in-frequent production.	Non-repetitive.	Non-repetitive (Linnik et al., 2013).
Fluctuations of capacity requirements			Low. The case indicated a stable workforce.	Medium (Linnik et al., 2013).
Material flow complexity	High. High variety in routings.		Low	
Takt time*	Minutes. 20 minutes	Hours. 80 hours.	Weeks.	Days or weeks. (Binninger et al., 2017, Vatne and Drevland, 2016)

4 Case study

In this chapter the two case companies are presented. Case company A is presented first in section 4.1, which contains a detailed description of their manufacturing processes and takt time based production. Some elements of their production planning are also included, before the current situation during the writing of this report is addressed.

Section 4.2 introduces case company B, where their takt time based production is explained and some elements of their production planning.

The chapter ends with a summary in section 4.3, where the various concepts related to the implementation of takt time are presented, before the characteristics of the two case companies are presented using the framework explained in section 3.1.3.

4.1 Case Company A

Case company A is a manufacturer of pressure vessels such as separators, scrubbers, knock-out-drums, reactors and slug catchers. In their facilities, located on the west coast of Norway, they can offer a complete manufacturing process – from design to delivery. Their customers are highly involved in the design processes. Hence, the company can be characterized as ETO. The manufacturing involves activities such as plate cutting, rolling, welding, assembly and non-destructive-testing (NDT), and the production holds around 20 employees in addition to contracted personnel. They also hold project management, engineering, procurement and project management.

The company position themselves as a manufacturer mainly of larger pressure vessels, with large material thickness. Their customers come mainly from the oil and gas industry, an industry with high quality requirements to procedures and materials. The average annual volume is around 16 units, however over the last decades, the company has experienced variances in terms of number of vessels produced per year, and the future demand of such vessels are somewhat hard to predict.

The oil and gas industry suffered from what is known in Norway as the “oil crisis”. The crisis came because of a dramatic fall in oil prices that led to a lack of profitability in the industry. This led to an increased focus on cost reduction, which had an impact on suppliers and subcontractors (Viken and Danielsen, 2017). This is also true for case company A, which had to downsize their working crew and devote more focus to efficiency, and cost reduction.

A takt system was implemented as a measure to reduce costs and lead time - which the case company consider as one of the most important strategic priorities in order to win contracts and remain competitive. The purpose of the takt system was to structure and balance the flow in order to provoke issues that earlier have been hidden. Areas on which to improve upon would be revealed and dealt with to better the efficiency – hence improving lead time and reducing costs.

Since the implementation of the takt system, the case company perceives that a better situational overview has been obtained, and that it has enabled them to identify challenges early, and initiate measures in time. For example, due to technical and capacity challenges new equipment and machines have been purchased. In addition, the improved overview of capacity helps the management to allocate resources and hire the appropriate number of external workers. In addition, case company A perceives that better discipline can be achieved, as a successful takt time requires that the workers are aligned with the plan. This promotes a shift towards a goal-oriented workforce and a continuous improvement culture.

The takt system was introduced in case company A less than a year before the writing of this report. Therefore, the following findings are from a relatively early stage of this implementation.

4.1.1 Manufacturing Process

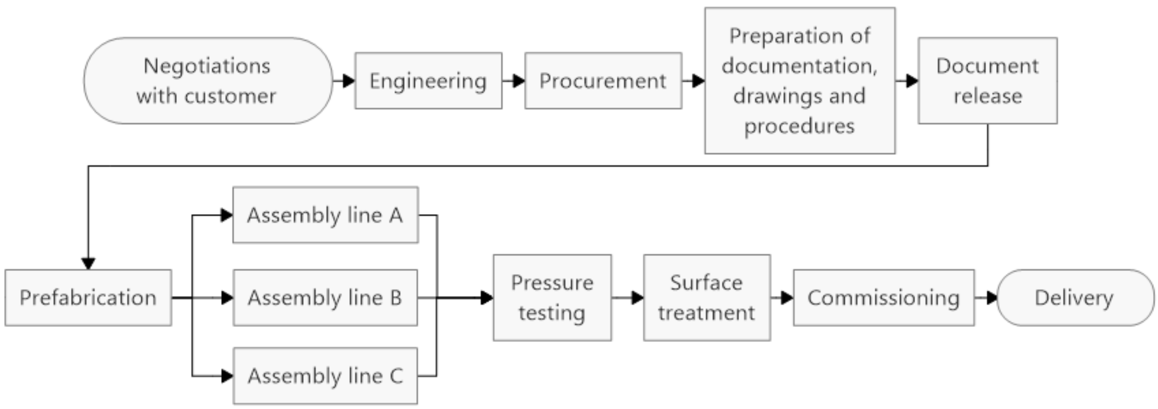

Figure 16: Simplified process flow

Figure 16 shows a simplified chart of the process flow. A project starts with negotiating between project management and the customer. Then the engineering processes begin, which can go through several design reviews depending on the requirements from the customer and the characteristics of the project. Procurement is initiated, as design elements are made ready and confirmed by the customer. Documentation and procedures are prepared before the production planning is initiated. When the customer confirms the final design, the project management releases the drawings and procedures. The manufacturing can commence. However, the projects are often subject to engineering changes which can delay the release of drawings, and further change schedules.

The main components are rings and heads (which together make the main body of the vessel), nozzles, brackets and mounts or skirts. A nozzle is a device that directs or modifies fluid flows and has often the shape of a pipe or a tube. A bracket is a component which is used to fix parts to together. Most of the parts are fabricated in-house, while other parts like the heads, machined parts and internals are purchased. The pressure vessels vary in terms of type, size and material. The complexity also varies from vessel to vessel; especially the material thickness and number of nozzles affects the required amount of work.

Figure 17: Pressure vessel with nozzles and brackets (With permission from case company)

The manufacturing process starts with pre-fabrication, where parts are made and sub-assembled. Rings are made from plates, which are cut, rolled and welded together to make the circular shape. Welds are tested using NDT-methods such as liquid penetrant or radiographic testing. The edges of the rings are grooved before they are ready for assembly. The throughput times for the pre-fabrication can vary depending on number of nozzles and other parts, material and thickness of the plates – the thickest plates can demand twice as much time as normal sized plates.

In the assembly area, the rings and one of the heads are welded together before the vessel is marked and cut. Nozzles and brackets are then fitted and welded to the vessel before the final head is welded on. Inspections and NDT are done throughout the assembly process – often at night, as radiographic testing requires clearance of personnel.

Figure 18: Assembly area. (With permission from case company)

After assembly and inspection, the vessel is pressure tested to assure that there are no leakages. The vessel is then surface treated and sometimes painted before final commissioning and delivery.

4.1.2 The Takt Time Based Production

There are three factors which made case company A eligible for takt time production according to the management. Firstly, there was an existing basic infrastructure with three rail lines in the assembly area, which allowed for three assembly lines. Having three lines reduces the variability within each line, as they can be assigned to certain product families of similar characteristics. Secondly, physical commonality; the products, although subject to variation, have some commonalities which allows to some extent predict the scope of future projects (product type, material type etc.). Thirdly, the manufacturing processes and their sequence are more or less the same across the product portfolio, although they vary in scope. This means that products can run through the system without drastically changing the setup. The two latter factors points towards that the manufacturing mix of case company A is homogeneous.

Three product families were made based on size, one for each line A, B and C. The largest vessels are put into line A, the smallest into line B, while line C contains the mid-sized vessels. Each line was separated into zones by dividing the available length of the lines by the length of a vessel representing each product family. The takt times were then found by dividing the estimated throughput time of the representative vessel from each product family, by the number of zones for each line. The takt system was designed to handle variation by using larger vessels from each product family to determine the zones and the takt times. This somewhat resembles the concept of takt capability, as the takt time calculation was based on a throughput time they were able to produce to.

Line A has three zones and a takt time of seven weeks per zone, which makes 21 weeks in total for the assembly. Line B has six zones, a takt time of one week, six weeks in total, and line C has four zones, a takt time of four weeks, which makes 16 weeks in total.

On the long term, the takt times are fixed, but the determination of the takt times is an iterative process. This means that it can be reduced or increased until an acceptable and fitting takt time is achieved. For example, the company aim to reduce the takt time for line A from seven to five weeks. This approach of determining takt time is fundamentally different from the traditional definition of takt time, as it is not based on demand. The volume is simply too low in order to calculate a takt time based on a backlog.

Even though the lines are divided with respect to vessel size, the vessels passing through one line differ from each other in terms of material type and thickness, number of nozzles and brackets. This leads to variance in required work and working hours. The more complex a vessel is the more work hours is required to complete the assembly in time, hence buffers are needed. Calendar-time buffers are baked into the takt time to complete the more complex vessels within the takt time. Capacity is also used as a buffer to cope with the variance in required work hours, this is managed by hiring external workers and adding extra shifts if necessary. In addition, unoccupied zones can also serve as buffers. For example, if a vessel is overdue it can be taken out of the line and put into available space. In this way, the vessel behind the late vessel, can be moved to the next zone as planned.

4.1.3 Production Planning

It is the planner, together with project managers and the production manager, who decides when, and in which line the vessels will start, based on the project deadlines. Long planning horizons enables the case company to plan the production schedule to somewhat level the production and avoid queuing into the lines.

Activities are somewhat specified to the different zones in the lines, but currently the activity packages are quite general and spans over several zones. It is the responsibility of the foremen to divide the activity packages and to assign them to the zones, while the planner specifies due dates, schedules and calculates the required work hours in Primavera – an enterprise portfolio management software, which case company A use to plan, schedule and control their projects. The required work hours are used as the base to hire in external workers. The planning is based on project progress (for example drawing release dates) and delivery deadlines. In addition, to achieve feasible plans, knowing the current status of ongoing activities is important, therefore progress reporting is an important input for the planning process. Technical drawings for the vessels are important to sequence the tasks correctly. This requires a technical understanding of the processes, as technical constraints limit the sequence flexibility. For example, welding heats up the material surrounding the weld, hence weld jobs cannot be done within a certain proximity to each other without considering cooling time.

Table 5: Takt time schedule (Based on case company documents)

WEEK	A1	A2	A3	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4
34	V A3	V A2	V A1							V C3	V C2	V C1	
35	V A3	V A2	V A1	V B1						V C3	V C2	V C1	
36	V A3	V A2	V A1	V B2	V B1					V C3		V C2	V C1
37	V A3	V A2	V A1		V B2	V B1				V C3		V C2	V C1
38	V A3	V A2	V A1			V B2	V B1			V C4	V C3	V C2	V C1
39	V A3	V A2	V A1				V B2	V B1		V C4	V C3	V C2	V C1
40	V A3	V A2	V A1					V B2	V B1	V C4	V C3		V C2
41		V A3	V A2						V B2	V C4	V C3		V C2
42	V A4	V A3	V A2	V B3							V C4	V C3	V C2
43	V A4	V A3	V A2		V B3						V C4	V C3	V C2
44	V A4	V A3	V A2			V B3					V C4	V C3	
45	V A4	V A3	V A2				V B3				V C4	V C3	
46	V A4	V A3	V A2					V B3				V C4	V C3
47	V A4	V A3	V A2						V B3			V C4	V C3
48	V A4		V A3									V C4	V C3
49		V A4	V A3									V C4	V C3

Table 5 serves as a simple example that illustrates the logic behind the takt planning for some imaginary vessels (the V stands for *vessel*, the second letter represents the line A, B or C, and the number is a vessel identity). The rows columns indicate in which zone the vessels are in a given week. The spreadsheet makes it easy to visualise when vessels are planned to move from one zone to another, and available space becomes easy to identify (the grey cells illustrates weeks with available space). The takt time control work as an area-planning tool, in addition to a production leveller by controlling the material flow into the assembly area.

Every week the production manager arranges a takt meeting together with the foremen, the planner and representatives from engineering and project management. This resembles the look-ahead planning from LPS which pulls resources into play (Emblemsvåg, 2014b). The purpose of the meeting is to look four weeks ahead, to examine if conditions are met to execute the assembly of a vessel and to solve any problems or deficiencies. The seven preconditions identified by Koskela (2000) is used (see section 3.2.2). If a condition is not met, the group discusses why and how to fulfil the condition. Hence, the meeting facilitates early identification of problems and challenges, which enables measures to be done before the problems actually occur. An example is provided in Table 6, which visualises how this is done for an imaginary vessel. The fulfilment of a condition is indicated by the number 1 in the column related to the condition. If a condition is not met, it is indicated with a 0, which also indicates that the assembly is not ready for execution.

Table 6: Four week look-ahead (Based on case company documents)

Position	Vessel	External	Preceding work	Materials	Info	People	Tools	Area	Comment	Execute
C1	V C4	1	1	0	1	0	1	1	Delayed materials, caused by cutting machine breakdown. Lack of competence of external workers. Arrange course	0
C1	V C4	1	1	1	1	0	1	1		0
C1	V C4	1	1	1	1	0	1	1		0
C1	V C4	1	1	1	1	0	1	1		0

Earned value method is used to measure project performance. During the initial project planning, a schedule with project milestones are set to form the baseline, which the progress reports are measured against. Scheduled performance index (SPI) and cost performance index (CPI) is used as key performance indicators to evaluate the overall efficiency of the project progress and cost. In addition, percent planned complete (PPC) is used to measure the completion of activities.

4.1.4 Current Status

The case company does currently experience low project SPIs and CPIs, meaning that they are behind schedule and over budget. They have also been somewhat inaccurate, as deviations between reported and actual progress have been identified. Activities which were actually completed, were not registered which led to wrong SPI and CPI. The case company is currently not performing the "Learning" planning level from LPS with root-cause analysis, such as 5 Whys to identify countermeasures and testing of countermeasures using methods such as PDCA (see section 3.2.2). The case company has also experienced challenges related to that surfaced issues and potential solutions are not communicated and dealt with. This lack of communication has been a barrier for continuous improvement, as workers perceived that there was no one listening to them when they reported about problems and potential solition. However, the trends are improving as the communication and reporting has improved, and workers are increasingly aligned with the new procedures.

The demand for the three product families have been relatively stable since the implementation of takt time, but some turbulence in product mix has led to changes in the takt time based production. Two extra-long vessels did not fit into either of the defined product families thus none of the takt zones either. The case company solved this by changing the setup for Line A and having two zones instead of three during the assembly of the extra-long vessels. When the vessels are completed, the takt time based production goes back to normal. The case company considers that turbulence in product mix might lead to changes in how the product families and takt time production is defined.

As already mentioned, the takt system has revealed issues. The assembly of the vessel shells is completed well within the takt time. The bottleneck has been the activities related to the nozzles; marking, cutting, fitting and welding. The case company are experiencing what they call "random variation" meaning that they do not know why they occur. This has led to build-ups in the lines and large schedule and budget deviations as there are high overconsumption of work hours.

The build-up in the lines has led to moving the shell assembly out of the first zones and completing them in the pre-fabrication area. This allows the nozzle-related activities to be further split up as the first zones in each line are no longer designated for shell assembly, and to move away large welding equipment which are only used for the shell assembly. During the writing of this report, this change was not fully implemented, but the company saw it as an opportunity to improve on the bottleneck activities.

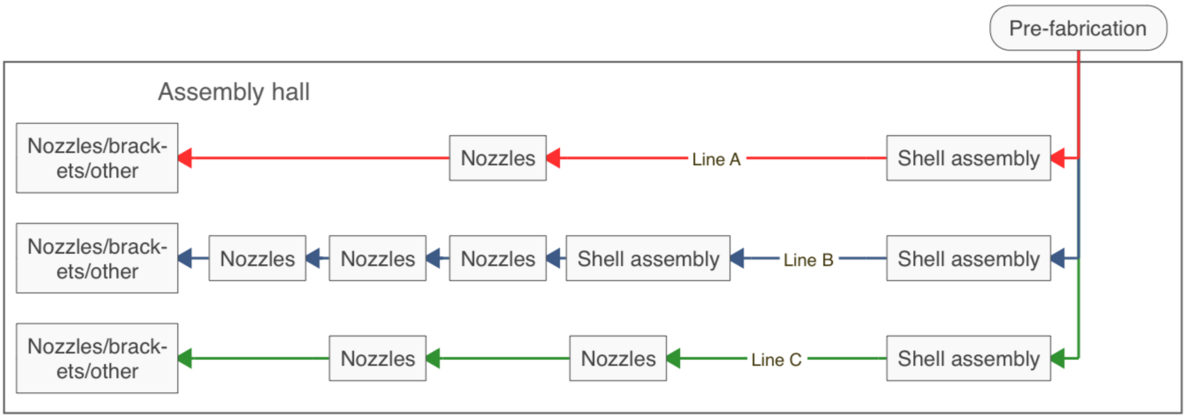

Figure 19: AS-IS layout

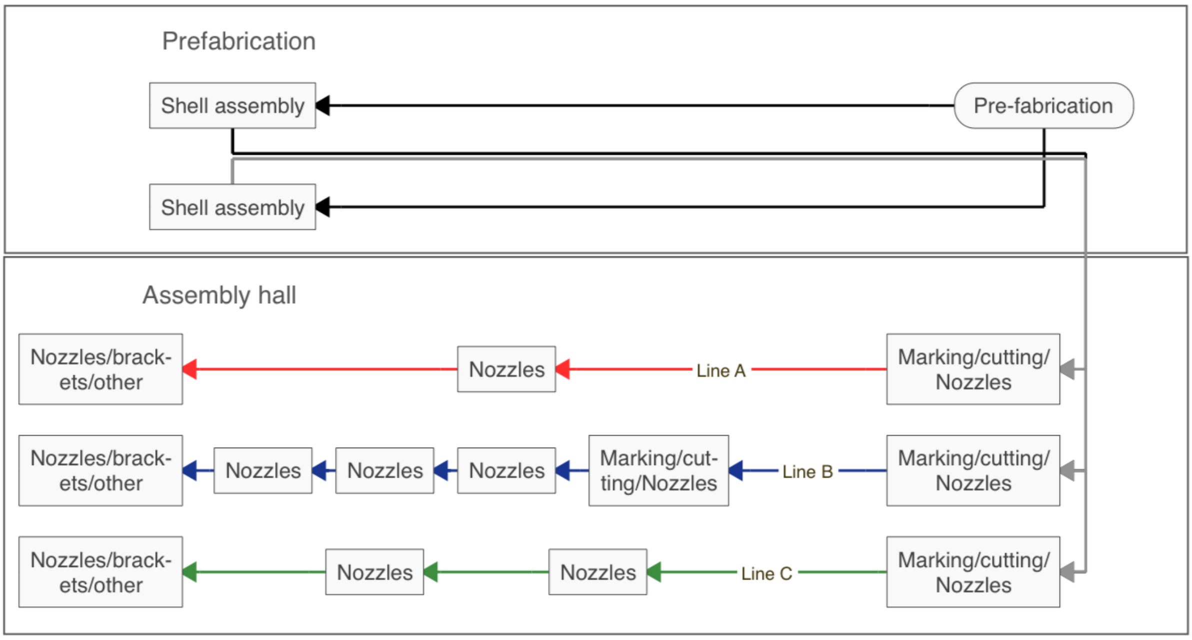

Figure 20: TO-BE layout.

4.2 Case Company B

Case company B is a manufacturer of equipment for the maritime industry. The equipment can be customized to meet the needs of an individual customer. The company have around 300 employees, and has an annual volume of about 200 products.

The company is planning to implement takt time in a sub-assembly line for their equipment. By implementing takt time, they seek to improve efficiency in the assembly line. Reducing the throughput-time can reduce costs and to improve planning. In addition, the takt time system is attended to improve the lead-time reliability, by ensuring that the products are ready in time for further assembly into the complete equipment. The demand situation is so that the volume is relatively consistent, and capacity for the assembly will be more or less fully utilized for the foreseeable future.

The products are constructed from thirteen different standard designs, based on product dimensions, but the products are not manufactured to stock, and production will only start when a customer order is placed. Around one third of the standard products are further customized and fabricated to specific customer requirements. These customized components are unique, quite work intensive and subject to engineering changes. Because of this, the sub-assembly line is considered to be MTO.

4.2.1 The Takt Time Based Production

Previous to the implementation of takt time, the case company had challenges concerning balancing the production to the capacity, and the workload was unevenly distributed from period to period because of changes in product mix. The flow was also complex, and products moved back and forth between the workstations, which made it challenging to get an overview of the flow and potential issues. By introducing line production, case company B aimed to improve the communication between the production department and planners. Takt time therefore became a natural tool to help balance the line and ensure a more even workload over time. In addition, the company saw that a flexible workforce was beneficial for takt time.

A simplified overview of the takt time production can be observed in Figure 21. Station 5 contains the most work intensive operations, and therefore has five resources available. Station 6 also has two resources available. The depicted days over the stations does not represent the takt time, but it is the maximum processing time for most products in each of the stations according to the experience of the foremen. For example, on station 1 most orders should be completed within one day. During the writing of this report the takt time was not yet explicitly defined for the production line, but was planned to be set based on the backlog with confirmed delivery times and available capacity.

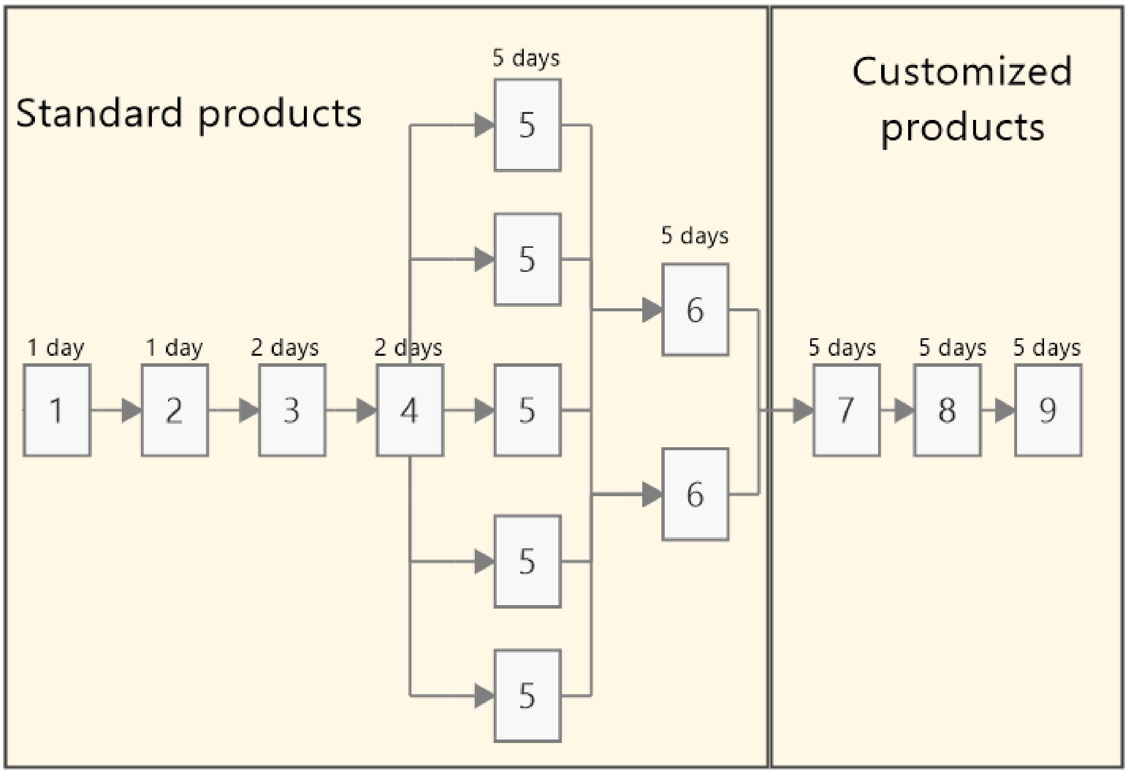

Figure 21: Takt time production, case company B. Based on company documents

4.2.2 Production Planning

The planning process somewhat changed with the implementation of the takt time system. Earlier the products were backwards scheduled, meaning that the production was planned so that the products were supposed to finish when they were due. However, in the new takt time system the company is going to use forward scheduling. This means that production will commence when there are resources available, and that there will be an ending inventory that will act as a buffer in case of delays. It also allows them to plan the production more independently from the rest of the production, and the production scheduling can be enhanced to further balance the production.

4.3 Summary

4.3.1 Concepts Identified from Case Study

Table 7: Concepts identified from case study

	Case company A	Case company B
Takt time determination	Definition of three product families. A relatively work intensive sample from each family was selected to calculate takt time, by dividing throughput of sample vessel by number of zones on the vessels line.	Takt time is calculated based on a backlog of customer orders.
Approach to takt time	Takt time controlled production system based on existing infrastructure with three rail lines. Physical commonality and repetitive process types facilitated for zone definition. The takt time determination is an iterative process. The company aims to reduce takt time as operations are improved.	Introducing line production was implemented to provide overview of flow, to surface issues and to improve communication between planning and production. Takt time is used to balance the line and the work load over time. The takt time controlled production was designed based on experience of the workers (foremen).
Product family	Three product families where defined based on size of the vessels (length and diameter). These families have their own assembly line. This grouping type makes it possible to have three vessels – one from each family, next to each other in the assembly hall.	Thirteen standards are used, but there is no separation between the standards in the line. Space constraints makes it difficult to separate flow between products.
Production levelling	Production levelling is not possible due to the high customer involvement in the production phase.	The production is a sub-assembly of the production of main equipment. This allows the case company to have an output buffer, and to sequence work orders to balance workload.
WIP buffers	Prefabrication and assembly of some vessels is done outside the takt time controlled assembly line. Available capacity is sent here to keep workers busy.	
Capacity buffers	External workers are hired in order to account for variability in demand and workload. A safety factor is used to calculate required hiring.	A flexible workforce allows workers to be sent to or from other departments if needed.
Time buffer	Calendar time is baked into the takt time in order to cope with variability in processing time.	
LPP	Lean Project Planning is used to improve reliability by using the seven conditions to ensure healthy jobs in the production. Foremen are involved in this process.	
Prefabrication	Components are prefabricated, which reduces the variability in process types in the assembly line.	

4.3.2 Characteristics of Case Companies

Table 8 summarizes the main characteristics of the case companies related to the framework of Buer et al. (2018) as explained in section 3.1.3.

In addition to the variables included in Table 4, four variables describing the levels of turbulence in design, schedule, product mix and volume are included. These variables were not included for the examples from literature, as the references did not provide sufficient information to determine the turbulence levels.

Table 8: Characteristics of case companies. Adapted from (Buer et al., 2018)

Variable	Case company A	Case company B
Product related factors		
CODP placement	ETO	MTO
Level of customization	Fully customer specific.	Offers thirteen standard designs that can be further customized to customer specifications.
Product variety	High	High
BOM complexity	Medium, between 3-5 layers.	Medium, between 3-5 layers.
Design turbulence*	High.	High.
Market related factors		
Demand type	Customer order allocation	Customer order allocation
Volume / frequency	Few large customer orders per year. Annual volume of about 16 pressure vessels. Long planning horizons enables the case company to avoid build-up in the production lines.	Few large customer orders per year. Annual volume of around 200 products, which is high enough to utilize the capacity.
Frequency of customer demand	Unique	Unique or sporadic. Orders of standard products may be repeated.
Schedule turbulence*	High. Engineering changes delays drawing release, and causes changes to schedules.	Medium
Product mix turbulence*	Medium	Medium
Volume turbulence*	High	Medium.
Manufacturing process related factors		
Manufacturing mix	Homogeneous. The pressure vessels go more or less through the same processes.	Homogeneous. The products go more or less through the same processes.
Type of production	One-of-a-kind production	One-of-a-kind production
Throughput time	Weeks. 6, 16 and 27 weeks for the small, midsized and large pressure vessels, respectively.	Days for standard products. Customised products have a much longer throughput time.
Batch size	Equal to customer order	Equal to customer order

Frequency of production order repetition	Non-repetitive production.	Non-repetitive production or infrequent production. Production of standard products may be repeated.
Fluctuations of capacity requirements	High. The company hires external workers to manage capacity fluctuations.	Medium.
Material flow complexity	Medium	Medium.
Takt time*	1, 4 or 7 weeks for small, midsized and large pressure vessels, respectively.	Days. Exact takt times are not defined, and will likely vary along with demand, as it will be based on a backlog.

5 Results

This chapter exhibits the results from this research, and it is structured according to the research questions. Section 5.1 exhibits a framework for the implementation of takt time based production control in HVLV manufacturing environments, which is the main result of this research. Results related to all three research questions are embedded in this framework. This section also contains the concepts that were identified through the literature and case study, related to research question 1. Section 5.2 will address the different approaches to determine a takt time, thus the results relates to research question 2. Finally, in section 5.3 the characteristics of HVLV manufacturing environments that apply takt time is presented, hence it contains the findings related to research question 3.

5.1 Framework for the Implementation of Takt Time in HVLV Manufacturing Environments

A framework for implementing takt time in HVLV manufacturing environments is proposed. The overall structure of the framework is depicted in Figure 22, and consists of four phases; *Collect information, Assess, Implement* and *Variability management and support.* The different phases will be discussed in the following chapters.

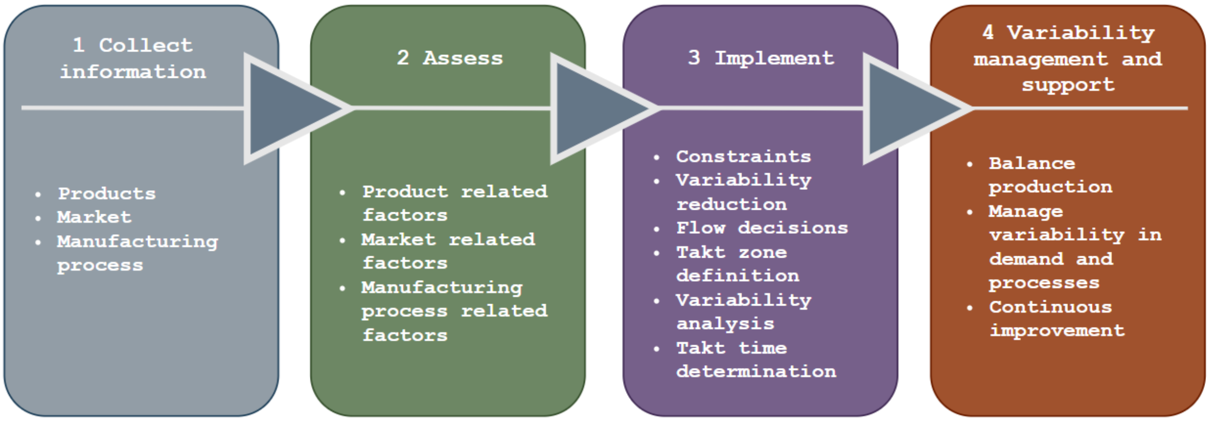

Figure 22: Framework for the implementation of takt time in HVLV manufacturing environments

The case companies validated the framework, as it corresponded with how they implemented takt time, and that the important elements were included.

5.1.1 *Phase One – Collect information*

The first phase concerns collecting information about the products, market and manufacturing processes related to the manufacturing environment in question. This information is fundamental for assessing the applicability of takt time in phase two, and to design the takt time based production in phase three. The three variables earlier used to describe HVLV environments is used here as categories.

Product information should be collected to facilitate for the determination of product families, and identifying constraints. Information should include data related to product type and function, required processing types and product characteristics.

Market information is collected to map the demand situation. Demand volume and demand frequency is useful to examine how variability should be dealt with, for example to determine is, and to what extent, buffers could be used to dampen variability.

Information related to manufacturing processes gives an overview of equipment and capacities, material flow, production processes and processing times. This information is vital for the definition of takt zones and takt times.

5.1.2 Phase Two - Assess

This phase is inspired by Tommelein (2017), who suggested the method for takt time implementation in construction. Based on the collected information in phase 1, it is possible to assess the applicability of takt time for a manufacturing environment. This information can be compared to the characteristics of HVLV manufacturers that apply takt time exhibited in section 5.3. This phase was included because takt time is not universally applicable to all manufacturing environments, or all parts of a manufacturing environments. Thus evaluating the applicability of takt time is important before an implementation process actually begins.

5.1.3 Phase Three - Implement

This phase concerns how the implementation process can be approached, using the different concepts presented in section 5.2. Figure 23 contains a structure of the implementation steps to visualise how the implementation process can be executed.

The design process starts by defining the constraints based on the collected information in phase one. These constraints sets the boundaries for how the different design elements can be applied. Next, variability can be reduced to facilitate for takt time before decisions related to the flow can be made. Next, the takt zones can be identified and work can be allocated to the zones. The variability analysis was included as it can be used to evaluate the preliminary setup and to visualize the variability i.e. by using operation balance charts. Variability reduction, flow decisions, and takt zone definition are showed in an iterative cycle, similarly to the method for takt time implementation in construction discussed in section 3.2.2. When an acceptable setup is achieved, a takt time can be determined.

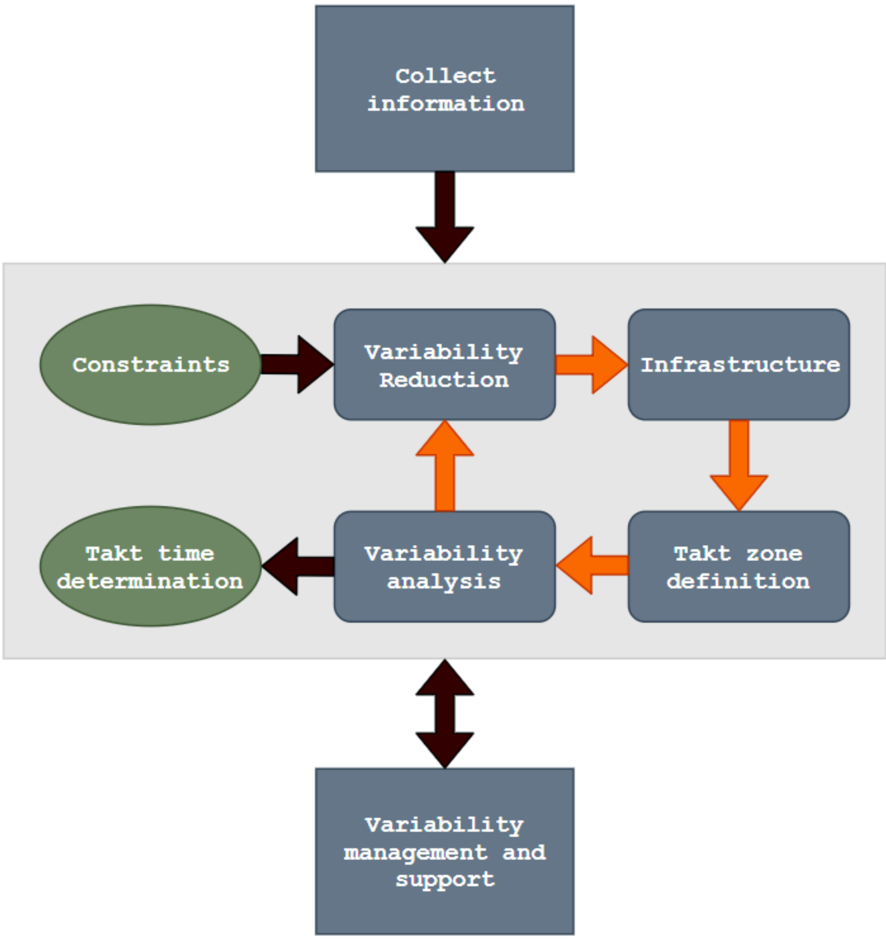

Figure 23: Framework for the implementation of takt time in HVLV manufacturing environments.

Six steps related to the takt time implementation process is proposed: *Constraints, Variability reduction measures, flow decisions, takt zone definition, variability analysis and takt time determination.* Each step, and its related concepts, is explained in Table 9, except the steps concerning takt time determination and the variability analysis, which will be addressed further in section 5.2.

The constraints were chosen as a step as these elements affects and limits how takt time can be implemented. For example, the infrastructure played a central role for case company A, as the existing rail lines in the assembly hall enabled them to apply line production without large investments. Comparatively, Ricondo Iriondo et al. (2016) could not apply line production as the existing infrastructure did not allow it, and new infrastructure was too expensive.

The category of variability reduction was chosen as reducing variability facilitates for takt time. As presented in section 5.1, a homogeneous product mix was common for all the examples of takt time implementation, and reducing variability can be used to achieve this homogeneity.

The flow decision step contains elements related to how the flow of products and workers are structured. How this is approached is related to the infrastructure and the setup of workstations and equipment.

Takt zone definition is central for implementing takt time as it dictates what should be done where. The constraints limit the amount and size of the zones, which further influences how takt time can be determined.

Table 9: Concepts for takt time implementation

Constraints	
Space/Infrastructure	Space limits the amount of working stations and the work they can exhibit, as well as the possibility to adjust the layout and infrastructure to facilitate for takt time. For example number of separated flows and number of takt zones can be constrained by space.
Level of industrialization	The flexibility of equipment to adapt for variability in processes and work load, and if the equipment is stationary or movable.
Products	Size and complexity of products limit how the products can be moved and treated. The sequence of process steps products must go through, dictates how and where work, equipment and workers are allocated.
Variability reduction measures	
Product families	Define product families to reduce variability within each family. Variability in work content should be less than 30%. Homogeneous manufacturing mixes facilitate for takt time, indicating that product families should be defined after processing type. If an overall manufacturing mix is obtained, grouping products after processing time can reduce variability in processing time.
Product family inclusion	Include product families with acceptable levels of variability in takt time-based production. Exclude product families with unmanageable variability.
Prefabrication	Prefabricate parts to reduce variety of process complexity in the takt time-based production.
Flow decisions	
Moving takt teams	If products cannot be moved, use moving takt teams that move between products according to the takt time.
Product flow	Stimulates surfacing of issues. Having more than one separated flow allow product families to be specified for product flow, which reduces variability within each flow.
Takt zone definition	
Zone definition and allocation of work and equipment	The number and size of zones. Allocation of work to zones to determine what should be done where.
Generalized takt time	Apply generalized takt time in the case of variability in routings.

The variability analysis step was included as it helps to evaluate how the takt time based production is configured and relates to a takt time. It can also give input to how it could be configured differently by visualising the location of potential bottlenecks and the extent of variability in processing times for different products.

5.1.4 Phase Four – Variability management and support

The last phase concerns concepts that can be used to manage the takt time based production over time. In Figure 23 one can see that the arrow also points back to the phase three. This is because the situation can change over time, which might require a change in the production system.

Table 10: Concepts of variability management and support

Variability management and support	
Production levelling	Sub-assemblies not on the critical path can be decoupled from the final assembly, by starting production when resources are available. An output buffer allows to level the production, depending on the size of the buffer.
Takt time grouping	Group products to create takt time groups of similar time buckets. To low volume or demand fluctuations can make this method difficult to apply. Infrastructure must also allow for more than one product per takt zone.
Capacity buffers	Use capacity buffers to cope with variability in processing times. Hire external workers to handle fluctuations in demand.
WIP buffers	Maintain WIP buffers to avoid capacity loss.
LPS/LPP	Use LPS or LPP to ensure reliability of operations by fulfilling criteria for initiation, and facilitate for continuous improvement in example by using PDCA.
Continuous improvement	Encourage workers to identify problems and suggest solutions. Make sure that surfaced problems and potential solutions are captured and dealt with to facilitate for continuous improvement, for example by using LPS or LPP.

These concepts, presented in Table 10, can be used to balance the production and manage variability over time, to support the takt time based production and to facilitate for continuous improvement.

5.2 How to Determine a Takt Time

Through the literature and case study, several different approaches were identified related to how takt time can be determined for HVLV manufacturing environments. These approaches are presented and explained in Table 11. In addition, the results related to the approach to calculate a takt time through a variability analysis is presented in section 5.2.1.

Table 11: Approaches for takt time determination

Takt time determination	
Calculate based on backlog	Takt time can be calculated by dividing effective working time by demand based on backlog. However, if demand fluctuates so does takt time, which is unfortunate for standardisation and improving operations.
Calculate takt time based on statistics	Takt time can also be calculated by applying basic statistics to historical data. Takt time can be set based on bottleneck operations, which other operations can be aligned to. Calculate a takt time for a product family by dividing the throughput time for a relatively work intensive product, and divide by number of zones.
Takt rate	Takt rate (psc/day or psc/week) can be used as an alternative to takt time in case of variability in demand and processing time.
Takt capability	Define the amount of work possible to produce. Can be used as an alternative to takt time when demand is variable or unknown.
Takt mode	Define sets of predefined takt modes to meet certain demand scenarios.
Time buffer	Use time buffers baked into takt time to cope with products with higher than average cycle times. Comes at the price of more waiting for less work intensive products.

5.2.1 *Variability Analysis*

Table 12: Key indicators from variability analysis

	Case company A	**Case company B**
Number of products	13	Around 205
Type of data	Planned working hours	Planned working hours
Sigma	2	2
Variability range for average process times between operations or takt zones	Line A: 94% Line B: 90% Line C: 88%	Zones 1-6: 52% Zones 7-9: 78%
Bottleneck	"Fit, weld" was the activity that exhibited the highest range of work content (>90%) and the highest average processing time.	Zone 4 was found to be the bottleneck for zones 1-6, with the highest average process time. Zone 8 was identified as the bottleneck for zones 7-9.
Share of operations exceeding takt time of bottleneck operation	Not defined. Operations are not specified to zones.	14%

A variability analysis was done for both case companies. The key results are exhibited in Table 12. Calculation of takt times was also done for both companies, using Equation 2, presented in section 2.3.

Data quality

There were challenges related to the data quality for both the case companies. For case company A the data availability was very low due to a change in work log and production planning systems. A very low data volume, only 13 vessels were acquired.

For case company B the data set was found inconsistent with lack of standardized work descriptions. This made it challenging to allocate the correct processing times with the working stations, and the different working stations contained a varying number of work orders.

Both the datasets were planned hours, as actual working hours were unobtainable due to inaccurate reporting.

Analysis for case company A

For case company A, the variability range for activities was very high, with between 88-94% for three lines. The "fit, weld" activities were identified as the bottlenecks for all three lines as they had the highest average processing time. However, the activities are not specifically allocated, and can be distributed across the zones. Included in the variability analysis for case company A, was a distribution matrix to distribute shares of activities to the takt zones. This tool was considered useful for the case company, as it indicated how much should be done in each zone. The share of each activity was distributed for each zone so that the total processing time for each zone was balanced. Table 13 depicts an example from line C, where the activities are distributed so the total processing time for each zone is balanced, as can be observed in Figure 24.

Zones	Mark, cut	Fit, weld	NDT Nozzles	NDT misc	Foundation + misc	int ext brackets	Total:	Takt time	Difference
1	1	0,07	0,07				83,77	125,50	41,73
2		0,43	0,43				85,74	125,50	39,75
3		0,43	0,43				85,74	125,50	39,75
4		0,07	0,07	1	1	1	87,85	125,50	37,65

Table 13: Distribution matrix for line C, case company A

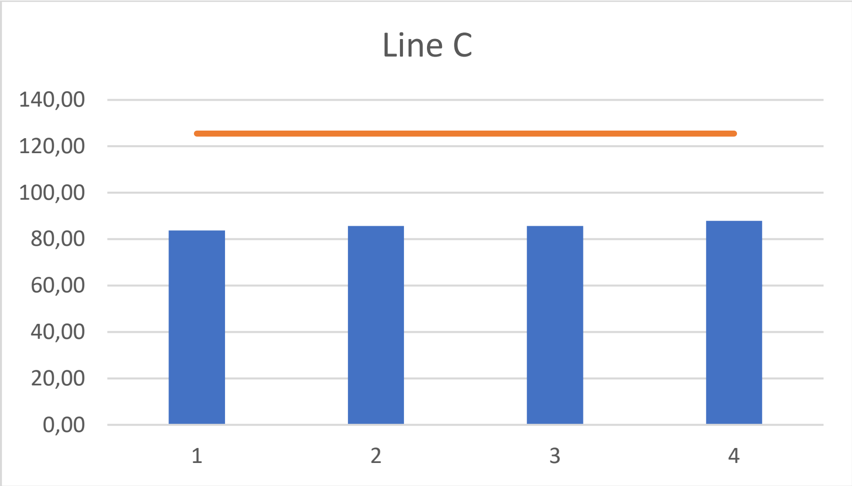

Figure 24: Operation balance chart for line C, case company A

The case company was generally positive to the suggested approach of calculating a takt time based on the variability analysis. But the low data volume made the takt time calculation difficult to derive any meaning from, as the representability of the data was questionable from the case company's point of view. In addition, the value of sigma was difficult to define explicitly, however the case company considered that it should be set low in order to put pressure on the activities' processing times and further stimulate surfacing of issues.

Analysis for case company B

For case company A, the activities could not be balanced across the line as they were specified for the takt zones. The variability range of average processing time between the takt zones were 52% for step 1-6 and 78% for zones 7-9. Zone 4 was identified as the bottleneck for zones 1-6 as it had the highest average processing time. For steps 7-9, the bottleneck was identified to be zone 8. An overview of the results of the variability analysis is depicted in Figure 25. Operation balance charts for zones 1-6 and zones 7-9 can be observed in Figure 26 and Figure 27.

It can be observed that zone 5 have higher an average processing time than zone 4, but this zone has five resources compared to zone 4 that has only one. In addition, zone 3 have a higher maximum range than zone 4, but a lower average processing time. Comparing the two operation balance charts, it can be observed that the customised products require much more work than the standard products. The variability is also much higher, as the range of work content in zone 8 and 9 is as high as 99%.

Zones	1	2	3	4	5	6	7	8	9
Number of orders:	224	219	216	147	214	213	63	89	211
Mean process time:	9,19	9,31	9,34	12,21	27,52	5,88	33,03	148,57	33,89
Standard deviation:	3,91	3,76	4,98	6,37	14,22	1,80	8,48	106,57	2,23
Range_max:	22	23	35	25	115	15	58	450	215
Range_min:	2	5	3,5	3	3	2	15	6	2,5
Variability	91 %	78 %	90 %	88 %	97 %	87 %	74 %	99 %	99 %
Nr of orders over takt	0	0	3	20	0	0	0	6	0
Share of order over tal	0 %	0 %	1 %	14 %	0 %	0 %	0 %	7 %	0 %
Set time	17,00	16,83	19,31	24,95	14,04	9,47	50,00	361,72	38,34
Takt time	24,95	24,95	24,95	24,95	24,95	24,95	361,72	361,72	361,72

Figure 25: Results of variability analysis for case company B. Screenshot from Excel spreadsheet.

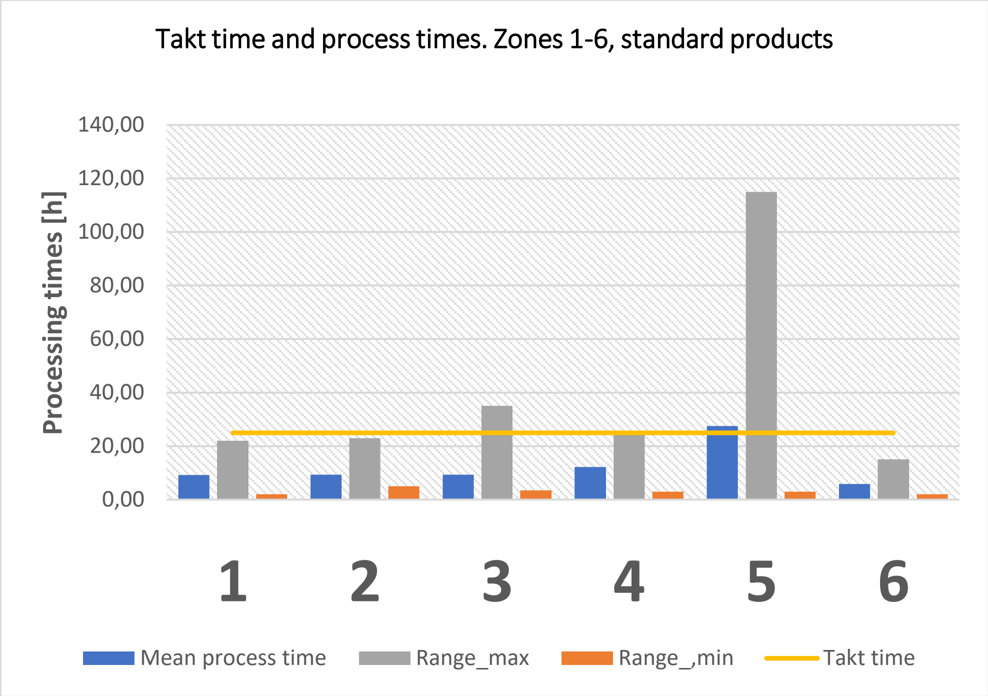

Figure 26: Operation balance chart for steps 1-6, case company B

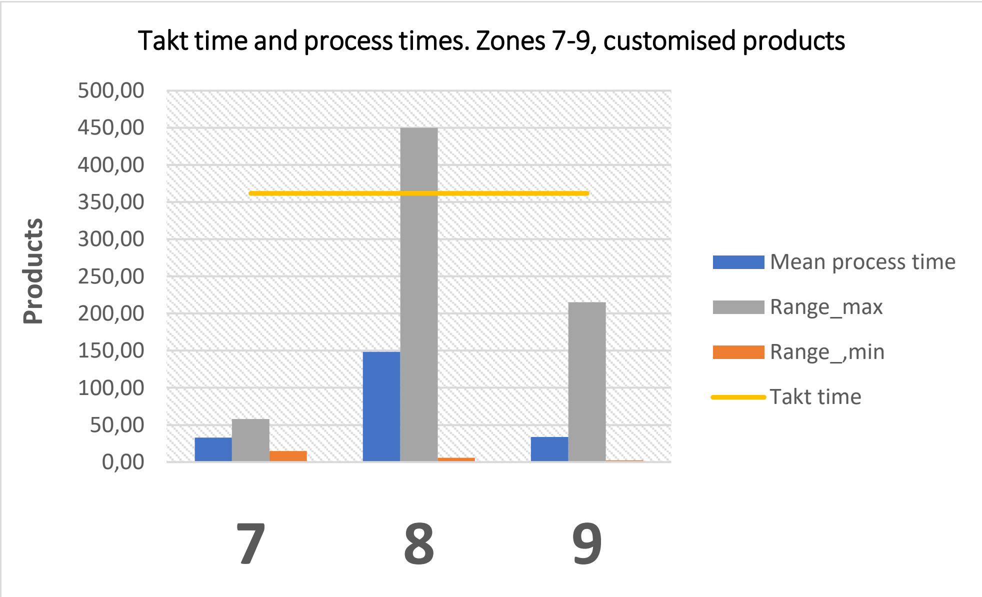

Figure 27: Operation balance chart for steps 7-9, case company B

The case company considered the variability analysis as helpful to get a better overview of the situation in the assembly line. It helped identify the bottleneck and where build-ups are likely to occur. The calculation of a takt time was also considered as a helpful reference point for calculating a takt time in the future. However, there were uncertainties related to the value of sigma and it was considered that this approach still somewhat relied on experience to decide how the sigma, and hence the takt time should be set.

5.3 Characteristics of HVLV Manufacturing Environments Applying Takt Time

Table 14 contains characteristics of HVLV manufacturing environments that apply takt time based production. These characteristics are synthesized from the characteristics identified in the literature study (Table 4) and the case study (Table 8).

For some of the variables, the examples exhibit a variety of characteristics. An example is the volume, which for case company A was as low as 16 products annually, which is very low compared to the other examples. The level of complexity in BOM and material flow was also found to be varying between the examples.

The level of turbulence was not discussed in the examples from literature. For the case companies the level of turbulence was somewhat different between the two. Case company A generally experienced higher levels of turbulence, long planning horizons enabled them to dampen the impact from this turbulence.

A homogeneous manufacturing mix is a common characteristic for all the examples' takt time based productions. In fact, some examples excluded products with high variability from the takt time based production.

Table 14: Characteristics of examples from literature and case study. Adapted from (Buer et al., 2018)

Variable	Description	Comment
Product related factors		
CODP placement	ETO or MTO	All studied examples could be characterised as ETO or MTO, or a combination of both.
Level of customization	Fully customised, or customisation based on standards.	The level of customisation varies between the different examples.
Product variety	High	The product variety is high for most of the examples.
BOM complexity	Low/medium/high	The studied examples exhibit very different BOM complexity.
Design turbulence*	Medium to high.	The level of design turbulence will increase with the level of customization. For both case companies the design turbulence is high.
Market related factors		
Demand type	Customer order allocation	
Volume / frequency	Few large customer orders per year.	Low volume and frequency for all examples. Volume varies, case company A had around 16 orders per year, compared to 200 orders for case company B.

Frequency of customer demand	Unique or sporadic.	Often unique orders, but some order repetition is considered for standard products.
Schedule turbulence*	Medium to high.	The level of schedule turbulence varies between the case companies.
Product mix turbulence*	Medium	Changes in product mix led to minor temporary changes in the takt time based production for case company A.
Volume turbulence*	Medium to high	Case company B, had relative consistent volume for the product. Case company A's annual volume varies from year to year. Long planning horizon for case company A enabled them to avoid order build-up.
Manufacturing process related factors		
Manufacturing mix	Homogeneous.	Mixed products are left outside the takt time based production.
Type of production	One-of-a-kind or small batch	One-of-a-kind production is the dominant type for the studied examples, one example of small batch production.
Batch size	Equal to customer order.	
Frequency of production order repetition	Non-repetitive or infrequent.	Non-repetitive production is dominant. However some infrequent production is considered for standard products.
Fluctuations of capacity requirements	Low/Medium/High	Varies between the different examples. Case company A had high fluctuations. Unknown for two of the examples from literature-
Material flow complexity	Medium to high.	Unknown for three examples from literature.
Takt time*	Hours/days/weeks	The duration of takt times varies largely between the different examples.

6 Discussion

This chapter discusses the results presented in the previous chapter. The chapter is structured according to the research questions. The proposed framework is discussed in section 6.1 along with the implementation steps; *constraints, variability reduction measures, flow decisions, takt zone definition* and *variability management and support.* Section 6.1 discusses the different approaches to determine takt time, and the variability analysis done for the two case companies. The final research question will be addresses in section 6.3, where the characteristics of the studied examples from literature and the case companies are discussed.

6.1 Research Question 1

How can takt time based production control be implemented in HVLV manufacturing environments?

According to the objective of this research, the framework should support the implementation of takt time in HVLV manufacturing environments. Firstly, the framework was constructed so HVLV manufacturers can approach an implementation process of takt time in a structured, easy-to-follow way, by following the suggested steps. Secondly, each step contains various concepts which can be applied in different ways to different contexts, so that the applicability of the framework corresponds to the diversity of HVLV manufacturing environments. Thirdly, the framework provides the means to evaluate the applicability of takt time in a HVLV manufacturing environments. Lastly, the framework proposes how takt time based production can be managed over time to achieve the benefits.

The framework expands on the method for takt time implementation for construction, by using some of its elements in the context of HVLV manufacturing, for example that the implementation process is iterative. The method for construction does not address the turbulence experienced in manufacturing, hence the framework included elements to cope with the related challenges. In addition, several approaches to determine a takt time was presented that can help to determine a takt time systematically.

The application of the various concepts included in the framework is likely to vary from case to case, given the versatility of HVLV manufacturing environments. In this section, each step with the corresponding concepts will be discussed and concepts will be compared with the case companies to generalize the application of the various elements.

6.1.1 Constraints

For the case companies, the constraints played an important role to how the takt time based production could be designed. The space and infrastructure at case company A allowed for three different lines, so that the product families they defined could be separated to cope with some of the variability in processing times. For case company B, on the other hand, there was only space for one assembly line, and product families could not be separated in the same way as with case company A. Also, the product families in case company A were defined based on size, because the available space could not allow three vessels with large diameter to be placed next to each other. This suggests that space and infrastructure are quite important constraints for designing takt time based production, as it limits how product families can be defined and how variability can be reduced. This also corresponds to the findings of Ricondo Iriondo et al. (2016), were the infrastructure did not allow for a paced product flow (see section 3.2.2.).

The equipment at case company A required manual input, thus became subject to variability from skill sets. Good welders can a welding job as fast as a robot, with a high welding quality, while other use much more time. This causes variability in processing time in addition to the variability caused by product variety, and larger buffers have to be maintained to cope with this variability. Having automated equipment can reduce variability in processing time, but can be less flexible in terms of moving equipment around. For case company B, the equipment was more or less locked to the workstations and could not be moved.

6.1.2 Variability Reduction Measures

Defining product families can be an effective measure to reduce variability, by separating products from each other. As homogeneous manufacturing mixes seems like an enabler of takt time, defining product families after processing types could be beneficial. However, the potential to define product families is limited by constraints. As earlier discussed, the product families for case company A had to be defined based on size. Since the overall manufacturing mix for case company A was homogeneous, grouping the products with regards to processing time could have reduced the variability in processing time, at the cost of lower space utilization as large and small vessels could be grouped together. For case company B the limited space did not allow to separate product flows in the same way as for case company A. Hence the less work intensive products become more vulnerable to increased lead-time as they have to stay in the same flow as more work intensive products.

If variability cannot be sufficiently reduced for some products, it should be considered to keep them outside the takt time based production. This is the case for case company A which have a separate assembly area to manufacture vessels with different characteristics than those in the takt time based assembly. This can also be used as a buffer in the case of excess capacity. For case company B, excluding product from takt time could be an option for the customized products which have higher levels of variability compared to the standard products, similarly to Ricondo Iriondo et al. (2016).

6.1.3 Flow Decisions

Moving takt teams can be an option if the constraints does not allow for product flow, for example if the equipment is stationary, or the products are too large to be moved. Even though case company A applies line production, they have the option to use moving takt teams, as most of the equipment is flexible enough to be transported around. For case company B, where the equipment is stationary, moving takt teams is not easily applicable.

A weakness of this research is that it does not go into whether moving products or moving workers is the most preferable approach. However, it can be noted that the literature included in this research indicated that a paced product flow is preferable, which is also backed up by case company A which argued that moving the products stimulated the surfacing of issues.

6.1.4 Takt Zone Definition

The definition of takt zones depends on the constraints and how the product families are defined. The size of the zones must be large enough to contain the larger products of the related product family, as well as the equipment needed. The number of zones is also constrained by size and infrastructure. For case company A, it could be beneficial to have more zones to reduce the takt time, especially for line A that has the longest takt time of seven weeks. But this is constrained by the product length and the length of the assembly line. It is considered that the surfacing of issues is less stimulated when takt times are very long, as more work has to be done within each takt zone. This can make it more difficult to keep an overview of the progress, especially when the progress reporting is inaccurate, which is the case with case company A.

The two case companies have quite different approaches to how the takt zones are defined. For case company A, the activities are not exclusively allocated to a zone. For case company B, the stationary equipment more or less dictates the allocation of activities to takt zones. In the latter case it is more difficult to balance the cycle times across the line for a product, as activities are fixed to zones. For case company A the activities can be distributed to balance the cycle times for across all zones.

In the case of variability in routings, generalized takt time can be used. With this approach, a takt time can be achieved also for product families of mixed products. However, this approach could come at a cost of underutilized capacity, as not all products require all process types. And if takt times are long, this underutilization becomes more prominent. Slomp et al. (2009) applied this concept in a setting were the takt time was given in minutes, compared to for example case company A which have takt times given in weeks.

6.1.5 Variability Management and Support

When processing times vary, the capacity requirements also varies which can be difficult to follow, and production levelling can help to deal with this issue. In general, production levelling is challenging for HVLV manufacturers because of the unstable demand and variability in work content. And managing the sequence is difficult to do without losing responsiveness towards the customers. However, the example from case company B shows that some levelling is possible when a sub-assembly can be decoupled from the main assembly, similar to what is proposed by Jina et al. (1997) (see section 3.2.2.). This means that some products will start and finish earlier which will increase WIP inventory, and some responsiveness can be lost in the case of engineering changes.

Takt time grouping can also be used as an approach to level the production. Millstein and Martinich (2014) applied the concept in a production environment with relatively high volume and throughput rates. And if production volume is to low, this concept can be difficult to do in practice. It is also constrained by space and equipment, as the takt zone must fit more than one product and must have the equipment to handle a variety of product types. For case company A, this approach could be beneficial because of high variability in process times, but the space constraints simply does not allow more than one vessel per takt zone. In addition, the long cycle times for the pressure vessels makes this concept infeasible.

Thus, for case company A production levelling is difficult to achieve. Their approach to deal with the variability in processing times is mainly using capacity buffers by hiring external workers depending on the planned workload. But it is considered that this approach has some disadvantages due to the variability in skill earlier discussed in section 6.1.1, and what the case company experience as random variation earlier discussed in section 4.1.4. Because of this, determining the size of the capacity buffer is challenging and could result in too much or little capacity. In the case of too much capacity, WIP buffers can be used to avoid capacity loss. For most of the examples included in this research, all activities are not done within the takt time based production. To avoid workers waiting on work, these "off-takt" activities can be used to keep the workers busy, hence cope with some of the challenges related to capacity. This corresponds with the findings of Faloughi et al. (2015) and Vatne and Drevland (2016).

LPS and LPP was included in this research because they can facilitate for the use of takt time. In the context of HVLV, complex products and engineering changes can cause disruptions in the production if for example workers or material are missing, or if there isn't sufficient information (drawings) to execute activities. The seven conditions here plays an important role, as they ensure that the production activities are healthy, i.e. that activities cannot be started without fulfilling all seven conditions. In addition, LPS and LPP can facilitate for learning and continuous improvement by comparing plans with what was actually done. Continuous improvement is important to achieve the benefits takt time was implemented for in the first place. Thus it is critical that problems that are surfaced with the help of takt time are captured and dealt with to prevent re-occurrence of the same problems. Similarly, possible solutions must be identified, involving those closest the problem (workers/foremen). This may contribute to inspire a continuous improvement culture which may further enhance the benefits of takt time.

6.2 Research Question 2

How can takt time be determined for HVLV manufacturing environments?

6.2.1 Takt Time Determination

Various different approaches to how a takt time can be determined have been proposed in this research. However, not all are considered equally applicable for all HVLV manufacturing environments.

Calculating a takt time based on a backlog of customer orders makes it possible to determine a takt time based on actual demand. When based on demand, takt time will change along with demand. And in HVLV, where volume turbulence can be high, takt time is prone to frequent variations which is unfortunate for standardization purposes and improving operations. This implies that this approach should be avoided in situations where large and frequent demand fluctuations causes large variability in takt time. This corresponds to what Liker and Meier (2006) argue (see section 3.2)

Determining a takt time based on historical data, provides a more stable takt time as it is based on average cycle times of products. By measuring variability, buffers can also be calculated to set a takt time that can accommodate products which are subject to variability in processing times. However, with this approach capacity loss is more likely to occur compared to calculating takt time from a backlog. The latter approach follows the changes in demand by adjusting the takt time, whereas a takt time based on historical demand remains more or less constant and gaps between low cycle times and the takt time becomes larger, especially when time buffers are applied.

Takt rate can be used as an alternative to takt time. However, it is considered that takt rate would not be applicable in HVLV manufacturing environments when volume is very low. If applied in case company A with a very low volume, the units would not be very convenient to follow. The rate would either have a very low unit per period, or the period would have to be very long.

Another alternative is to use takt capability, but as this approach is given in terms of product mix and volume, it is difficult to establish in a situation with a wide product variety and varying processing times. Related to the takt capability, there is the concept of establishing takt modes to meet certain demand situations. But instead of defining the modes as takt capabilities, it can be interpreted as a specific takt time which could be applied in a certain situation. This approach could for example be applied for case company A, and the two extra-long vessels that were fitted into line A. A takt mode could be established for the situation were the line must accommodate products which does not fit into the normal takt zones.

6.2.2 Discussion of the Variability Analysis

The variability analysis as a tool to assess the takt time based production was helpful, as the various performance indicators revealed issues, and it visualised how the various products related to a takt time through operation balance charts. The charts revealed where there likely would be excess capacity, and where bottlenecks could occur. Because of the variability in processing times, it is not certain that the bottleneck is the same for all products. By studying the results of the analysis, it was possible to determine the zone which was most likely to be the bottleneck. In an environment with high variability, it can be difficult to determine what exactly will happen, but through analysing historical data it is possible to indicate what is likely to happen. This can be useful to determine what operations which should be improved first, and where resources should be allocated.

The calculation of a takt time through a variability analysis had some limitations. Some of the aim of the variability analysis was to analyse historical data in order to say something about how the future can be expected, and from that calculate a takt time. For case company A, the low data volume increases the influence of extreme samples that questions the representability of the data. For case company B, the data volume was much higher but the inconsistency also made the dataset less reliable. For both case companies the obtained data were defined in terms of planned working hours, and it is considered that actual hours would represent the reality better and absorb more of the variability experienced in actual processing times. Thus, to improve the reliability of the variability analysis, the data should have been based on actual progress measurement, standardized data categories and larger data volumes.

For both case companies, a sigma-value of 2 was selected. A takt time should be set high enough to absorb some variability in processing times. Simultaneously it should be set low enough to increase discrepancies which stimulates the surfacing of issues and improvement of operations. How to find the correct balance between these two arguments was difficult to determine through the variability analysis. Therefore, what the value of sigma should be, remains unanswered, and it is considered that elements of experience and trial-and-error is needed by using this approach to determine a takt time. This further amplifies the notion that the determination of a takt time is an iterative process.

Despite the limitations, it is considered that the takt time calculated for case company B could be implemented for zones 1-6, as the variability in average processing time was relatively low considering that product families were not separated from each other. The variability in the zones for the customized products was much higher compared to the standard products, where zone 8 had twice as high a maximum range than zone 9. This have some similarities with the example from Ricondo Iriondo et al. (2016) discussed in section 3.2.4, and the case company could consider if the assembly of the customised products should be controlled with takt time, or if the assembly process should be configured differently.

A surprising benefit of the variability analysis was that it facilitated for the allocation of activities in takt zones for case company A. In this way the variability analysis could aid the foremen when they allocate work to zones, by suggesting what amount of work to be done where.

6.3 Research Question 3

What variables influences the applicability of takt time for HVLV manufacturers?

The findings from this research related to research question one can be beneficial for HVLV manufacturers that considers to implement takt time for their production. The variables gives a framework to assess the applicability of takt time, and can be compared to the examples of HVLV manufacturers that has applied takt time.

The characteristics exhibited in Table 14, shows that takt time can be applied for a variety of HVLV manufacturers, which have different sets of characteristics. This indicates that the applicability of takt time could be broader than one might think, given the origin of takt time from non-repetitive environments. In non-repetitive environments, takt time is defined in terms of seconds or minutes, but when applied to HVLV manufacturing environments the duration can be much longer, such as for case company A that has the longest takt time of seven weeks. This suggests that takt time could be applied for HVLV manufacturers of larger and work intensive products.

However, manufacturing mix seems to be an important variable, as all of the studied examples from literature, and the two case companies, had a homogeneous product mix, and products with to high variability in work content was left outside the takt based production. Mixed products that require a high variety of processes complicates the use of takt time, as variability in routings and processing times increases. Hence, product families that requires similar processes are more applicable for takt time compared to mixed products. For case company A, the pressure vessels are homogeneous, and they require the same type of equipment and skill. Combined with prefabrication, the processing time becomes the primary subject of variability in the assembly line, which the company can manage through hiring external personnel.

All of the studied examples were characterised with low volumes, and perhaps the most extreme example is case company A, who only had an annual volume of 16 orders. This suggests that low volumes do not make takt time inapplicable. However, the volume must be seen in relation to how it is distributed, as volume turbulence in HVLV suggests that demand is not evenly distributed. In takt based production, production enters a zone for every takt beat, and if demand volume increases this might lead to queues into the takt zone which again can cause extended lead times. For case company A, long planning horizons enables them to respond to this volume turbulence.

The product variety was high for all the studied examples, and combined with turbulence, variability in processing time is likely to occur for HVLV manufacturers. This implies that takt time will mainly provide lead-time reduction for the more work intensive products in a family, as the products with higher cycle time will dictate the duration of the takt time. Less work intensive products in a family will have lower cycle times than the takt time, which causes the longer lead-times than necessary for these products. This somewhat contradicts with the purpose of takt time to reduce lead-time, and implementing takt time can cause a trade-off between reducing lead-time for some products, and extend it for others. Hence defining product families correctly is important to minimize extended lead-time for less work-intensive products.

6.4 Limitations

Firstly, a weakness of this research is that the framework has not been tested. Although it was validated by the case companies, the versatility of HVLV manufacturing environments indicate that other HVLV manufacturers in different situations could have other opinions. In addition, the framework was highly based on the subjective understanding of the author, which can make the reliability and generalisability of the framework questionable.

Secondly, the interviews could be subject to bias. The interviewee were persons that chose to implement takt time in their manufacturing environments, thus some optimism for the concept in general could possibly create a barrier for critical perspectives.

Thirdly, the research found that production levelling could be done for sub-assemblies that could be decoupled from the critical path, such as for case company B. However, the research did not examine how this could be done and the potential implications it could have on the performance of the takt time based production.

Fourthly, the characterisation of HVLV manufacturing environments, and the examples of takt time implementation was done using a selection of variables, rather than the entire set of a framework. This selection was made through the understanding the author had on the topic. Thus, there might be other variables that could have provided different results compared to what is presented in this research. In addition, the variables related to turbulence were not assessed for the examples from the literature study, as the references did not discuss these issues. This is considered as a weakness of this study as lack of information makes it difficult to generalize the impact of turbulence on takt time. Further, the timeframe of this study limited the depth of investigation of the turbulence at the case companies. A deeper study into this matter could have revealed other details and aspects than those discussed above.

Finally, the case study was based on only two cases. It is considered that a larger number of cases could have improved the research for generalisation purposes. The HVLV is an umbrella term of manufacturing environments that exhibits a different sets of characteristics. Thus, more case studies could have further validated the applicability of takt time in HVLV manufacturing environments.

Some of these limitations can be dealt with by more research on the topic, which can further validate and establish the validity of takt time in HVLV manufacturing environments. Suggestions for further research will be presented in the next chapter.

7 Conclusion

In this chapter, the conclusions of this research are presented, along with contributions to theory and practice. This is followed by suggestions for further research.

The objective of this research was constructed based on that the research on takt time in HVLV manufacturing environments is scarce, and that more empirical studies are needed to make generalised conclusions on the applicability of takt time in HVLV environments. In addition, the literature did not clearly show how HVLV manufacturers could implement takt time in a systematic way, hence hampering the development of empirical research. This led to the development of a framework, which could support adoption of takt time in HVLV manufacturing environments and facilitate for further empirical research.

The research problem and objectives led to the three research questions that are repeated here:

1: How can takt time based production control be implemented in HVLV manufacturing environments?

2: How can takt time be determined for HVLV manufacturing environments?

3: What variables influences the applicability of takt time for HVLV manufacturers?

In this research a framework for the implementation of takt time in HVLV manufacturing environments is presented, and it encompasses the findings related to all three research questions. The research provided two main contributions to theory and practice. 1) The framework provides a systematic methodology that can support practitioners in HVLV manufacturing in the implementation of takt time. A variety of concepts are included, which corresponds to the diversity of HVLV manufacturing. This can further expand the pool of empirical data on which further empirical research can be conducted. 2) The framework provides the means for practitioners of HVLV manufacturing to assess the applicability of takt time for a manufacturing environment.

The framework presents an approach to how takt time can be systematically implemented for HVLV manufacturers, through four phases: *Collect information*, *Assessment*, *Design* and *Variability management and support.*

In the first phase information concerning products, market and manufacturing processes should be obtained. This information can be used to assess the applicability of takt time in a HVLV manufacturing environment in phase two. Phase two relates to research question 3, and it was found that takt time can be applied in a variety of HVLV manufacturing environments. However, the variable concerning manufacturing mix was found critical, as homogeneous manufacturing mix was found to be common enabler of all the empirical examples. In addition, because of variability in cycle times HVLV manufacturers could potentially have to make trade-off decisions between lead time reductions for work intensive products versus increased lead time for less work intensive products.

The third phase answers both research question 1 and 2. Takt time can be implemented through six steps: *Constraints*, *Variability reduction measures*, *flow decisions, takt zone definition*, *variability analysis* and *takt time determination.* Each step encompasses different concepts that can be used in an implementation process. These concepts are not universally applicable to all HVLV manufacturing environments, and the composition of concepts will likely vary from case to case.

Various approaches to determine a takt time was identified, and their applicability depends on the variability in demand and processing times. In general, three guidelines are recommended: 1) avoid fluctuations in takt time, 2) set takt time high enough to buffer against some variability in cycle times, and 3) set takt time low to increase discrepancies and stimulate improvement. The first point indicates that calculating a takt time from demand, or a backlog can be unfortunate if the variability in demand and work content is high, as takt time will vary along with demand. The second and third point oppose each other, and a balance must be found to cope with variability and simultaneously stimulate surfacing of issues that can be dealt with to improve efficiency.

Further Research

Research similar to the approach presented in this thesis, can be conducted to further establish and expand on the framework. By studying more examples of takt time implementation in HVLV manufacturing, other aspects and perspectives can be identified, due to the diversity of HVLV manufacturing, and the variety of different approaches to takt time implementation.

The framework should be tested in order to validate its applicability. By using the framework in an actual implementation process of takt time, the structure and logic of the phases and implementation steps can be verified and potentially improved. Through testing, the applicability of the suggested concepts can be specified for different segments of HVLV manufacturing. Further research can be conducted on how a takt time can be systematically determined for HVLV manufacturers, and how to balance between buffering against variability and stimulating surfacing of issues.

Research can be conducted on the implications on production levelling for takt time based sub-assemblies, to identify possibilities, challenges, and guidelines to how it should be done.

Finally, further research on which variables that influences the applicability of takt time in HVLV manufacturing, can be done by studying more examples of HVLV manufacturers that exhibits different characteristics than those presented in this research.

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Appendix

Appendix A - Planner at case company A.

Purpose: Collect data concerning work hours for activities per vessel. The aim of this data collection is to look at variability for the different activities, and by assigning the activities to takt-positions one can analyze the variability of work hours for every position. The hypothesis is that this can be used to systematically select a takt time by using statistics.

Questions	**Time**
Introduction	5 minutes
Thank you for the interview	
Explain purpose of interview	
Data collection	10 minutes
How are activities grouped/standardized?	
How are activities assigned into the current takt-positions?	
Activity planning	15 minutes
How are activities planned? • How are work durations estimated? • What are the variables? • Is the process standardized? • How much experience is needed?	
What is the reliability/predictability of the plans? • What activities are considered reliable? • What activities are considered unreliable, or more subject to variations? • Why can be causes of unreliability?	
What do you do to improve planning and estimates? • What data is recorded? • How is the data recorded?	

Appendix B – General manager at case company B

Purpose: These questions concern mapping how the takt system at case company A was developed.

Questions	**Time**
Introduction	5 minutes
Thank you for the interview	
Explain purpose of interview	
Characteristics of case company	10 minutes
What is your annual volume?	
How many workers have you employed?	
Can you describe your products? - Are there any standards? ○ How many? What are they based on? How are customers involved in the production process?	
How is the demand situation? How is demand distributed?	
Development of takt time based production	25 minutes
What characteristics made case company A interesting/eligible for Takt? Under what circumstances would Takt be unfit for case company A, if any?	
How was your approach to create a takt time production system? • What steps were taken? • Was it somehow systematic? • What information was used? • Who were involved? • Was there any challenging part of the takt system development?	
What was your approach to define the area for takt production? • Why three lines? • How did you define the product families? • What data was used? • Why the different number of zones in the lines?	
How important was experience in this development? • Could “anyone” have done this?	

Appendic C - Transcription of interview with case company A – 15.03.2019

Participants:

- General Manager
- Production Manager
- Chief of Engineering

Summary:

The option to look at the 5% of their product portfolio to see how it can be managed in a takt based production system is no longer perceived as relevant for the case company.

The takt system is working well in terms of identifying problems and bottlenecks, which are dealt with to improve the production processes.

The assembly of the rings are mostly done within time, and most welding processes are also done more or less as planned. However, the case company is experiencing what they call "random variations" for the marking and cutting processes, meaning that they do not know why they occur. There are large mismatches between planned and actual task durations, which leads to large budget gaps. They want me to investigate why these variations occur, how it affects the takt system and how it can be dealt with. Possible solutions can be to change the takt system by changing number of zones or the takt time, or managing the processes in order to keep the takt time. They suggest that I observe the processes by following teams or foremen to understand the variations.

Transcription in Norwegian:

GM: Sidan vi prata førige gong, har det skjedd mykje. Det vi slit med er pålitelegheit på noko av utstyret vårt, slik at vi slit med å få gjennomført dette på den måten vi tenkte.

Interviewer: I forhold til dei store tankane?

GM: Tja, det har vore flest problem med nokre av dei litt mindre tankane, men vi hadde for eksempel kuttemaskina som braut ned og då kom mykje rart.

Production manager: Erfaringa vi har gjort er at vi har tvunget fram der vi ser bottleneck'en. På dei alle fleste tankane vi har bygd i dag, har gått igjennom hall 1. Det er berre ein tank som ikkje har gått igjennom der med tanke på segresjon. Og det vi ser er at om ein ikkje klarar å halde tida eller få opp effekten for å presse på nedover, så har vi sett at vi egentlig får ei linje til i hall 2 der, med ei eigen sammensetning av skall. For fram til skallsamansetninga så går det ganske bra med tanke på tid. Men når vi skal byrje å sette hol på tankane og sette inn mulige braketter og stusser så går tida mykje lengre enn planlagt, og så får vi ei opphopning. Dette havariet med kuttemaskina gjorde det heller ikkje noko betre.

GM: Med det eg tenkjer med litt av settinga her – vi har jo ikkje komen så langt som vi håpa, men vi har på mange måtar fått avdekt ein del ting å fikse. Slik sett fungerar (takt) systemet som tiltenkt, fordi at litt av poenget var å framprovosere ein del ting som måtte fiksast, og det har nok dukka opp. Og vi har invensteringsmidler som vi skal bruke til å løyse noko av det, men vi klarar ikkje å få løyst alle problema så fort som vi håpa. Eller for å sei det på ein anna måte; det var fleire problem enn det vi trudde.

Production manager: Vi ser eigentleg to områder; vi har assembly-linja i hall 1 der tankskall er ferdig og... (Production managerdett ut)...

GM: Det må vere hall 1 tenkjer eg, men det går kanskje an at ein ser på korleis det er og så ser vi på også korleis det kan bli.

Production manager: For det vi har sett, i tillegg til at det tar lang tid, er dette med plassen i hall 1 er utfordrande ift. å ha tre linjer.

GM: Vi slit med midtlinja fordi det er så mykje utstyr som må rundt desse store tankane.

Production manager: Ja, i tillegg til desse store endebunnane som kjem oppi der.

GM: Men alt dette er berre slik som den rotete virkeligheita eigentlig er. Det er viktig at du er klar over det. Her er mykje vi fiksar på og jobbar med å fjerne. Og så tvilar eg på om at vi kjem i mål i 2018(19?).

Production manager: Hovudsaka er at vi har fått avdekt mange ting. Utfordringer, utstyr – type utstyr, type design, type stuss vi vel på dei ulike kategoriane som kan vere med på å gjere oss meir effektiv. Og det er slikt som ein må jobbe med over tid. Det vi ønskjer er få få ned transporten som ikkje gjer oss noko produktivitet. Fordi vi må opp med produktiviteten vår når vi jobbar på tanken. Det er egentlig å finne ut når vi har høgare og når vi har lågare (produktivitet). Alt ifrå at ein flyttar på ting, at ein går inn og ut av lageret.

Interviewer: Det trengs ein kartlegging?

Production manager: Det er mykje som kan kartleggjast for å legge om måten ein gjer ting og når ein gjer det. Då vil ein sikkert sjå mykje, vil eg tru. Ein ting er å ha orden i roten, men om ein har rot i systema blir det enno verre. Mykje å hente der.

Interviewer: Ser ikkje heilt korleis eg skal spisse oppgåva mi inn mot dette. Men for å ta det med desse 5%-tankane. Er det slik at dette ikkje var like nyttig likevel?

GM: Vi har ein tank i denne kategorien, men den kjem til å rusle ut av produksjonen. Og vi veit ikkje når neste gong vi får inn ein slik type case. Men den delen løser vi, det er ikkje det som er problemet. Vi må finne ei løysing på dei 95%. Fordi ein ting er å få takt-systemet opp og gå reint metodisk, men det er så mange praktiske ting som må løyses. Det er eit studie i seg sjølv – alt i frå flyt og maskiner og vi heldt på med å gå igjennom heile maskinparken vår også. Fordi ein kan ikkje ha ei taktlinje der ein har for eksempel to posisjoner som er avhengig av ein spesifikk type maskin og så har ein berre ein. Det er slike ting vi oppdagar, blant anna. Vi har for eksempel berre ein plasma-kuttemaskin og om to tankar treng den samtidig blir det vanskelig. Og når det attpåtil klikkar då blir det endå verre.
Production manager: Det er også relatert til tjukkelse på materialet.

Interviewer: Slik eg forstår det så går det bra med samansetning av skall, men så blir det problem for å få ned tid på markering og kutting?

Production manager: Så lenge forutsetningene ligg til rette – material er på plass etc, så går det rimelig greit å valse og sette saman ringane og det er der vi kan hente inn tid for å spare inn tid til buffer i andre enden - for der slit vi. Og det er frå skallet er satt saman, og ein skal merke der ein skal lage hull og ein skal lage geometrien til der ein skal sette inn stussen til det er ferdig sveist, det er der det er utfordringane våre i dag. Normalt er skal-samansetning 5-6 veker.

Interviewer: Noko eg har vurdert å gjere, er å måle variasjon i dei ulike linjene. Og få ut ein graf på korleis arbeidsmengda endrar seg over tid i dei ulike sonene.

Production manager: Men vil du då avdekke noko eg er interessert i? For eg får ulike svar; når ein treng å vere ein person, når ein treng å vere to personar på dei ulike operasjonane.

GM: Men dette er skills; fordi vi ser at det varierer veldig på kor lang tid dei treng til å kutte hull på desse stussane. Og også i forhold til type stussar, somme typar stussar klarar dei relativt fort, andre heldt dei på med i vinter og år. *Det som har gitt oss utfordringar er at det er for mykje tilfeldige variasjon på spesielt merking og kutting av stuss-hola.* Slik at å finne ut kva som er rotårsaka her, dét hadde vore veldig interessant.

Production manager: Sveisen går greit, det er til ein kjem dit at vi har utfordringar. Så er det den evige diskusjonen med kva posisjon tanken skal stå i når ein kan sveise kva. Kor mange angrepspunkt har ein. Der får eg fire-fem ulike svar utifrå kva for ein formann eg spør. For dei skal sveisast frå topp til ned, og då er det kor mange arbeidarar kan ein ha inne i samme posisjon i forhold til retninga ein kan sveise i. Og det kan sikkert sei noko om kvifor det er ein bottleneck når ein kjem så langt, om ein har ei begrensning – om ein kan ha maks to eller tre personar på. Sveisetida går an å regne ut utifrå tjukkelse etc. Det er kor mange ein kan sette på som er begrensinga i løpstida.

Interviewer: No er dette ei litt anna vinkling enn det eg hadde sett for meg i utgangspunktet, så eg er litt forvirra.

GM: Du skjønar det at det er bevegelige mål vi jobbar med. Så då blir det litt sånn.

Interviewer: Eg prøvar å finne ut korleis eg skal angripe dette her. Men eg har forsåvidt tenkt å sjå på dette med variasjon, og å sjå på det de kallar for «tilfeldig variasjon» kan vere interessant.

GM: Den er jo ikkje «tilfeldig» i «the ultimate sense». Men den er tilfeldig i forhold til kvar vi er no, vi klarar ikkje å sjå mønstera i det ift. planlegging.

Production manager: Vi slit jo sjølv om det er ti eller 60 stusser på ein tank. Så klarar ikkje vi å estimere tida nøyaktig nok til å sei når vi er ferdig.

Interviewer: Fordi det er så mange variasjonar?

Production manager: Det er veldig mange variablar som speler inn, både på type stuss og plassering og tjukkelse og ein enkel ting som skills på arbeidarar – kva dei kan og ikkje kan. Og litt av grunnen er at våre eigne tilsette er multitaskarar og dei er litt her og der og bistår med å innleie operasjoner (spesielt dei vanskelige).

Interviewer: Korleis er det med framgangsmåling no? Er det meir nøyaktig no?

GM: Vi har tidene, men ikkje på enkeltoperasjoner. Men vi har for eksempel innsetting av stuss X. Då veit vi kor mykje tid som har gått til merking, kutting og sveising. *Og vi veit også i forhold til budsjett, og der er det store sprekkar, på enkelte ein sprekk på 200%.*

Production manager: Men det er på aktivitetane mark, cut, fit, weld.

GM: Og slik sett hadde vore veldig nyttig å fått kartlagt for å kunne gjort noko med dette problemet. Slik at sånn oppgåvemessig, så tenkjer eg at du må skrive om kva som var tanken med systemet innleiingsvis og kor langt vi har komen, og at det fungerar med tanke på samansetting av skall. Men når vi kjem til innsetting av stusser så er det for mykje tilfeldig variasjon til at vi klarer å holde takt-tidene. Og for å løyse det, kan ein då sjå på sånn og sånn og sånn.

Production manager: Vi ser det jo på look-ahead også. Det er komplisert nok.

Interviewer: Det kunne vore interessant å sett på. Som eg har nemnd tidlegare har eg tenkt å sjå på dette med variasjon – korleis ein kan redusere/kontrollere variasjon for å fasilitere for takt. Slik eg forstår det er der problem at det er ein såpass variasjon at ein ikkje fasilitetar for takt.

GM: Og då er det fleire moglegheiter: Vi kan *auke taktlengda*, vi kan *auke antal stasjoner* og det tredje er at vi *gjer noko med prosessen* slik at vi klarar å halde takta. Og alle desse tre kan du sjå på. Du kan ha funne ut at gitt x antal stasjoner og produkt slik og slik, så må vi ha takt-tid på det og det for at vi skal klare å halde takta. Det er eit svar. Eit anna svar er at om vi skal klare å halde den takta vi vil ha, så må vi kanskje auke antal stasjoner – og det kan vi gjere ved å flytte den eine linja, slik som vi no gjer, ved å flytte den inn i hall 2.

Production manager: For det gjer vi tidvis i dag. Det var ikkje plass i hall 1, så då byrja vi å sette saman i hall 2 då såg vi effekten at vi kom kjappare i gang med å sette saman skallet, men så er det når ein kjem til fasen ein skal skjære hull.

GM: Og den siste er å sjå på slik det er, og undersøkje kva som skal til for å halde takta. Er det meir utstyr? Er det fleire folk? Betre skills? You name it. Så det er ganske mange interessante problemstillingar her.

Production manager: Vi diskuterte seinast i går dette her med teikning -forståing av dokumentasjon ein skal arbeide etter. Det er viktig. Det har vore ein diskusjon, der teikningane ikkje er bra nok osv.

- (19:30 – 22:30 praktisk om datainnhenting)
- **End of interview**

Appendix D – Summarized interview guide for case company B

Questions to case companies
Introduction
Thank you for the interview
Explain purpose of interview
Characteristics of case company
What is your annual volume?
How many workers have you employed?
Can you describe your products? - Standardization? How? - How are customers involved in the production process?
How is the demand situation? - How is demand distributed?
Data collection
How are activities grouped/standardized?
How are activities assigned into the current takt-positions?
Activity planning
How are activities planned? • How are work durations estimated? • What are the variables? • Is the process standardized? • How much experience is needed?
What is the reliability/predictability of the plans? • What activities are considered reliable? • What activities are considered unreliable, or more subject to variations? • Why can be causes of unreliability?
What do you do to improve planning and estimates? • What data is recorded? • How is the data recorded?
Development of takt time
What characteristics made case company B interesting/eligible for Takt? Under what circumstances would Takt be unfit for case company A, if any?
How was your approach to create a takt time production system? • What steps were taken? • Was it somehow systematic? • What information was used? • Who were involved? Was there any challenging part of the takt system development?
What was your approach to define the area for takt production? • How did you define the product families? • What data was used? Why the different number of zones in the lines?
How important was experience in this development? Could "anyone" have done this?

Appendix E – Communication with case companies

DATE	COMPANY	DESCRIPTION
11.03.2019	**B**	Visit at company. Tour in production facilities. Meeting where case company was presented, and data collection was planned.
15.03.2019	**A**	Interview – see appendix C
25.03 – 04.03	**A**	Company visit. Interviews, meetings and observations in production facilities.
04.03	**A**	Workshop with company concerning findings related to the visit, and discussion around framework and variability analysis.
02.05	**B**	Interview concerning framework and variability analysis.
14.05	**B**	Interview with production manager concerning validity of framework and variability analysis