Evaluation of Manufacturing Cost Models

- An evaluation of manufacturing cost models for an assembly line and an evaluation of a data collection method

Matilda Garbe, Rebecca Olausson

LUND
UNIVERSITY

Department of Industrial Production, Lund University, 2014

Abstract

The manufacturing industries struggle to keep up with the global competition that is spreading. In order to be able to deliver a product at the right time, to the right price and at the same time stay profitable it is essential for companies to increase the efficiency of their manufacturing system and to reduce costs. Plenty of manufacturing cost models have been developed to help companies for this purpose and one of these models is *manufacturing cost deployment (MCD)*, developed by Yamashina & Kubo, which focuses on reducing waste and losses. It is a method to investigate the relationship among cost factors, i.e. the processes generating costs. MCD was implemented two years ago at Volvo Construction Equipment (VCE) in Wroclaw, a company assembling backhoe loaders. The method has yet not been successful and is a loss in itself since it has become more of an administrational task with scarce results.

One of the data input sources VCE uses for MCD is the output of a method called work sampling. It is a raw data collection tool to gain knowledge in the distribution of value and non-value adding activities in the assembly. This method has been tested briefly without considering the accuracy of the results. Without knowing the reliability of the data attained from work sampling it can be discussed whether it should be used as a source for MCD, or for any other evaluation of a production process for that matter. Without reliable input it is impossible to get reliable results.

This thesis investigates how MCD is used at VCE to gain a deeper understanding of the problems concerning the method in order to give recommendations for a better implementation of the model. Investigations are also made to see if there is an alternative manufacturing cost model suitable for VCE. The work sampling method is examined to determine the reliability of the results generated. The studies have mainly been conducted through interviews, literature reviews and participation in preparations and execution of work sampling at VCE.

One of the main issues with MCD at VCE today is the lack of dedication. Without dedication it is hard to achieve the desired results and this is something they need to work with. MCD consists of six matrices, but only the first three of them are used at VCE and both the B and C matrices contains deficiencies of relevance. Furthermore, the B and C matrices need to be updated and standardized.

An alternative manufacturing cost model that would be suitable for VCE is the *systematic production analysis*, developed by Ståhl. The purpose of this method is to identify the loss terms of quality, downtime and production rate. It is a user-friendly method with a strong focus on improvement work through eliminating deviations.

Regarding the reliability of using work sampling as a source of data, it is essential that the assessors are aligned to avoid different interpretations of the observations. Another aspect of importance regarding reliability is the selection of operators, machines and stations; these need to be representative for the line. The more observations made, the better the accuracy of the results. Using confidence intervals ensure accurate results and observations need to be made randomly. If all of the above criteria is fulfilled the results from work sampling can be seen as reliable.

Sammanfattning

Företag inom tillverkningsindustrin kämpar för att hålla jämna steg med den globala konkurrensen som ständigt ökar. För att kunna leverera produkter vid rätt tidpunkt, till rätt pris och samtidigt skapa lönsamhet är det av största vikt för företag att öka effektiviteten och sänka kostnader. Under årens lopp har flera olika kostnadsmodeller utvecklats för att hjälpa företag i detta syfte. En av modellerna är *manufacturing cost deployment* (MCD) som utvecklats av Yamashina & Kubo. Det är en metod som används för att undersöka sambandet mellan kostnadsfaktorer; processer som generar kostnader och förluster. MCD implementerades för två år sedan på Volvo Construction Equipment (VCE) i Wroclaw, dock utan större framgång. Idag är metoden snarare ett administrativt arbete än ett verktyg för att sänka kostnader på grund av uteblivna resultat av metoden.

En del av de data som är input till MCD kommer från work sampling, en metod som används för att beräkna tidsfördelningen mellan olika aktiviteter. Denna metod är också relativt ny för VCE och har bara testats två gånger utan vidare reflektion över hur noggranna resultat som erhålls. Om inte tillförlitligheten på de data som metoden genererar är känd så kan det ifrågasättas huruvida den ska användas som datakälla för MCD. Utan tillförlitliga input är det omöjligt att få tillförlitliga resultat.

I denna studie undersöks hur VCE använder sig av MCD för att få en djupare förståelse för varför implementatinen av metoden inte fungerar, samt för att ge rekommendationer på hur de kan förbättra arbetet med metoden och på så sätt få önskvärda resultat. Då MCD inte är den enda kostnadsmodellen kommer även andra modeller att undersökas i syfte att finna en alternativ metod och klargöra på vilka sätt den skiljer sig från MCD. Dessutom undersöks även work sampling för att avgöra hur tillförlitliga resultat denna metod kan generera. Studierna har huvudsakligen genomförts genom litteraturstudier, intervjuer och medverkande i förberedelser och utförande av work sampling på VCE.

Ett av de största problemen med MCD idag är brist på hängivenhet. Utan tro på metoden är det svårt att få önskvärt resultat och detta måste VCE jobba med. MCD består av sex matriser, men endast de första matriserna används och då det finns stora brister i både B- och C-matrisen behöver de stora förbättringar. Ett annat problem är bristen på standardisering för hur kostnader ska beräknas, vilket omöjliggör jämförelser av resultat från MCD.

En annan modell som skulle passa bra för VCE är den *systematiska produktionsanalysen*, utvecklad av Ståhl. Syftet med denna metod är att identifiera förluster i termer av kvalitet, stilleståndstid och taktförluster. Det är en användarvänlig metod med starkt fokus på förbättringsarbete.

Gällande tillförlitligheten för work sampling som datakälla är det av yttersta vikt att de som utför observationerna tolkar aktiviteter på samma sätt. Andra aspekter att ta hänsyn till är urvalet av operatörer, arbetsområden och maskiner; dessa måste vara representativa för produktionslinan. Ju fler observationer som görs desto högre blir noggranheten. För att säkerställa att noggranheten blir tillräckligt hög kan konfidensintervall användas för att räkna ut minsta antalet observationer som krävs. Observationerna måste utföras slumpmässigt. Är alla dessa kriterier uppfyllda så kan resultaten från work sampling ses som tillförlitliga.

Acknowledgements

This thesis is the final part of our Master of Science degree in Mechanical Engineering at the Faculty of Engineering at Lund University. The thesis has been conducted at Volvo Construction Equipment in Wroclaw, Poland.

First, we would like to express our gratitude to our kind and considerate supervisor, Tomasz Maleszka at Volvo Construction Equipment. Your sincere commitment, guidance and exceptional support have been priceless. We would also like to thank Tommy Bengtsson and all personnel at VCE, not only for their hospitality and enthusiasm, but also for their time and effort spent on helping us and we wish them all the best and good luck in the future.

Finally, we want to dedicate special thanks to our supervisor at the Lund University, Jan-Eric Ståhl, for his valuable comments, ideas and support.

Lund, September 2014,

Matilda Garbe & Rebecca Olausson

List of Acronyms

VCE	Volvo Construction Equipment, in this thesis VCE refers to the plant in Wroclaw, Poland.
MCD	Manufacturing cost deployment, in this thesis the manufacturing cost reduction program developed by H. Yamashina & Kubo.
VPS	Volvo Production System
VA	Value adding
S-VA	Semi-value adding
IMPM	Integrated manufacturing performance measure
SPA	Systematic production analysis, a manufacturing cost model developed by J-E. Ståhl.
PPM	Production performance matrix
DT	Downtime
TBF	Time before failure
MTBF	Mean time before failure
MDT	Mean downtime
Work sampling	Data collecting method used for measuring time utilization.
QRPS	Quick response problem solving

Table of contents

1 Introduction

This initiating chapter begins with the background of issues associated to the subject in general. The problem description is clarified followed by the purpose of this thesis. Finally, the report outline is presented.

1.1 Background

The manufacturing industries struggle to keep up with the global competition that is spreading. Manufacturing organizations seek to produce high-quality products faster and to a competitive price due to the increasing competitiveness. In order to be able to deliver the product at the right time, to the right price and at the same time stay profitable it is essential for companies to increase the efficiency of the manufacturing system and to reduce costs. To be able to reduce costs the companies need to find out why and where costs incur. Plenty of manufacturing cost models have been developed to help companies for this purpose. One of these models is *manufacturing cost deployment*, developed by Yamashina & Kubo, which focuses on reducing waste and losses.

Many investigations suffer from inadequate and incorrect data, argue Doganaksoy & Hahn [1]. No matter what model companies use, the crucial part of every method is to have correct, adequate data input to get reliable results, since the analyses can only be as good as is the data upon which they are based. As the saying goes; - *Shit in, shit out*. The essence is having standardized and successful methods for collecting data and to measure accurately to achieve reliable data input. It is commonly thought that the data required is just there, but knowing what data is required and how and when to collect it is more challenging than one could assume. One data collecting method that is used at Volvo Construction Equipment, Wroclaw (VCE) is work sampling, a method to measure time distribution of activities. The method has existed for several years, but it can be questioned whether or not it is a reliable source of data.

1.2 Problem description

VCE has in the previous two years conducted two loops of Yamashina and Kubo's MCD model, but without success. MCD is a quite general model and the design and how it is best implemented depends on the type of industry and factory. Hence, MCD needs to be customized for each plant using it. The benefit for VCE of obtaining better results from MCD can be used as an argument for a bigger budget for solving the problems identified through MCD. Finally, MCD could result in cost reduction and if so, the method will have achieved success.

One of the data sources used for the MCD at VCE comes from work sampling. This method has only been tested briefly without considering the accuracy of the results. Without knowing the reliability of the data gained from work sampling it can be discussed whether it should be used as a source of data for MCD, or for any other evaluation of a production process for that matter.

1.3 Objective

The objective of this thesis is to investigate how MCD is used at VCE and to gain a deeper understanding of why it is not working properly in order to be able to give recommendations for a better implementation of the model at VCE. Investigations will be made to determine if there are other cost manufacturing models that could suit VCE in their strive to optimize and reduce costs. If there is another model that will be suitable for VCE it will also be investigated how it differs from MCD.

As part of the objective the work sampling method will be examined to determine how reliable results the method generates.

1.4 Research questions

To achieve the objective, three research questions have been formulated. The first question concerns manufacturing cost deployment, the second other manufacturing models that could be applied on VCE and the last concerns work sampling.

1. How can VCE improve their work with MCD?
2. Is there another manufacturing cost model, apart from MCD, that would be suitable for VCE and if there is, how does it differ from MCD?
3. Can work sampling be seen as a reliable source of data when evaluating production processes?

1.5 Delimitations and focus

Due to the time constraints for this thesis the focus has been on the assembly department at VCE, i.e. the logistics and quality departments at VCE are excluded from this thesis.

Regarding the first research question there are many types of manufacturing cost models and to find all of them and evaluate whether they could be suitable for VCE would be too time-consuming for this thesis. Jönsson [2] has in his PhD thesis presented twelve different manufacturing cost models, which will be the starting point for the third research question.

1.6 Report structure

This is a comprehensive thesis and all chapters might not be of interest for all types of readers. Therefore, a brief description of each chapter is presented for readers to easily orient themselves in the report. Since the two first research questions can be treated separately from the third, the two first ones are treated in one chapter and the third in another chapter to make it easy for the reader to follow. The thesis has the following structure:

Introduction	The introduction gives a brief background of the issue, including problem description, purpose and delimitations of this thesis.
Volvo	This chapter includes the history of Volvo, a description of VCE and the current situation at VCE, Wroclaw.
Methodology	In this chapter facts and discussions of several approaches and methods are provided to justify the chosen methodology for this thesis. The procedure of the thesis is also presented. Readers without interest for how the thesis was conducted can ignore this chapter without losing the contents of the report.

Manuf. cost models	The first two research questions are addressed in this chapter. The theory behind MCD is presented as well as the evaluation of MCD at VCE and potential improvements. Other manufacturing cost models are presented and compared with MCD and finally a description of how the alternative method can be implemented.
Work sampling	This chapter treats the third research question. The theory behind work sampling is described as well as how it has been used at VCE. Together with theory and the participation in work sampling conclusions about the reliability of work sampling as a data source are drawn.
Conclusions	This chapter concludes the answers to the research questions and the chapter ends with a proposal for future research within this area.
Future visions	Achieving improvements from manufacturing cost models results in increased unbalanced lines of the stations and therefore this chapter proposes how the line balance can be enhanced.

2 Volvo

The aim with this chapter is to introduce The Volvo Group and Volvo Construction Equipment in general as well as the factory in Wroclaw, where this thesis has been performed.

2.1 Volvo history

The very beginning of the Volvo history starts already in the 18th century with a man called Johan Theofron Munktell. He worked as a foreman in a coin factory in Eskilstuna, Sweden, and was an initiative and creative man who had many projects. One of them was starting a beer brewery so that his employees at the coin factory would drink beer instead of the 2.5 liters of hard liquor they drank every week during work. Not surprisingly, this resulted in better health and improved working ability for the employees.

After leaving the coin factory, Munktell went on a study trip to England. This is where he got inspiration and knowledge to start a production of locomotives. Later, in 1853, Munktells Mekaniska Verkstad delivered the first locomotive in Sweden.

When Munktell left the coin factory, a man named Jean Bolinder replaced him. Together with his brother Carl Gerhard, Bolinder once again followed in Munktells footsteps and went to England learning more about molding and workshops. A year later they came back to Sweden and started their own workshop. Later on, Munktell and the Bolinder brothers merged their companies into AB Bolinder-Munktell.

In 1913 Munktell created the first tractor in Sweden. This was a big step towards the development of Volvo Constructions Equipment. Volvo was created in 1927 and in 1950 they acquired Bolinder-Munktell. To mirror the acquirement and strengthen the Volvo identity, the company later changed the name into Volvo BM AB [3].

2.2 The Volvo Group

Volvo was divided into two divisions in 1999, when Volvo Cars was sold to Ford Motor Company. The other division, The Volvo Group, still has its headquarters in Gothenburg, Sweden. The company is a manufacturer of trucks, buses, construction equipment and marine and industrial engines which are all divided into the business areas; Volvo Trucks, Mack, Renault Trucks, Volvo Buses, Volvo Penta, Volvo Aero and finally Volvo Constructions Equipment [4].

The Volvo Group has about 110,000 employees and production facilities in 19 countries with products sold on 190 markets. The net sales of The Volvo Group in 2013 were SEK 273 billion [5].

The company culture at The Volvo Group is called The Volvo Way and it expresses the culture, behavior and values at the division. The Volvo Way is based on the conviction that “every individual has the capability to improve our business operations and the desire to develop professionally” [6]. The core values are quality, environmental care and safety. These values have been a tradition since a long time ago and according to the organization, the company culture has become a unique asset, which is hard for competitors to copy [7].

2.3 Volvo Construction Equipment, Wroclaw

The assembly line for backhoe loaders (BHL) in Wroclaw started in 2002. A BHL has a loader unit in the front and an excavator unit in the back, see Figure 2.1. The factory has 210 employees at the moment. The BHL that is assembled in Wroclaw was designed from a blank sheet of paper with direct input from backhoe customers around the world. There are two models of BHL's, BL61B and BL71B. The later model has a larger engine and stronger hydraulic pumps compared to the previous. One machine consists of around 2,100 parts, requires around 3,000 operations and has a lead time of three days. Each day six machines are assembled and during high season up to twelve machines are assembled. To customize the machine there are 150 options [8].

Figure 2.1 exhibits a backhoe loader [*9*].

2.4 The Volvo Production System

The Volvo Production System (VPS) is a common basic system for employees within The Volvo Group. It is both a framework for manufacturing operations and a toolkit including methods such as Lean and Six Sigma [10]. The VPS Academy ensures that the system is introduced and used within The Volvo Group. The aim of using VPS is to achieve world class performance, to create value for customers, for the employees and for the owners. This is accomplished by securing quality, delivery times, safe and environmentally-sound workplaces, reducing waste and using best practice [8]. The five principles for VPS's vision are [10]:

- *Process stability* - reduce variability and waste and strive for predictability and efficiency.
- *Teamwork* – all employees are part of the improvement process.
- *Built-in quality* – doing things right the first time.
- *Just-in-time* – the right thing on the right place at the right time.
- *Continuous improvement* – a long-term approach to always improve the processes.

The VPS model consists, apart from the five principles, of the customer and The Volvo Way.

Apart from ensuring the use of the VPS, the VPS academy also assess the performance level at all plants in the Volvo Group, recommend improvement opportunities and how to implement them to reach the next performance level [11].

3 Methodology

This chapter aims to explain the research methods and to justify each choice of methodology used in this thesis. First, the scientific view and research method is presented, after which the validity, reliability and credibility of the work is discussed.

3.1 The scientific view

Depending on from what view a research study is performed different methods can be used and different results gained. Therefore, it is crucial to account for the view used. Arbnor & Bjerke presents three different approaches that have been generally accepted; the analytical view, the systems view and the actors view [13]. All of the views differ in how the reality is perceived. Below is a brief introduction of each view.

3.1.1 The analytical view

According to Arbnor & Bjerke, the analytical view presumes that the reality is filled with facts and that it is the same regardless who observes it [13]. The reality can be seen as summative and all the parts in it make the whole. This means that by understanding the parts, conclusions about the whole system can be drawn. It is important for the researcher to influence the researched object as little as possible when applying the analytical view. Also, when applying this view it is common to use quantitative data for the analysis.

3.1.2 The systems view

Unlike the analytical view, reality contains subjective opinions of such structures, except from fact-filled structures that are objective, and those are also treated as facts in the systems view. Due to this, Arbnor & Bjerke argues that the reality is not summative. While the analytical view treated the parts of the systems as independent of each other, the systems view takes into considerations the potential synergies, or the negative effects, that can occur when parts interact [13]. Therefore, it is important for the researcher to try to understand the interactions between the different parts in the system. Both quantitative and qualitative data are used for the analysis when applying a systems view.

3.1.3 The actors view

The actors view presupposes that the reality is a social construction. To understand the whole system it is of great importance to study the single individuals and to understand their behaviors according to Arbnor & Bjerke [13]. When applying the actors view it is common to use qualitative data. The researcher participates in the observation as one of the parts in the social construction. The result gained when using this method is thereby dependent on the researcher and his or her social context.

3.1.4 The scientific view of this thesis

The scientific view chosen is the systems view, which considers different parts of the system to interact and affect each other. Considering the method work sampling the human factor needs to be taken into account since it is based on observations made by humans. Also, considering the research regarding MCD and other manufacturing models, much of the work is made manually and the human factor needs to be taken into account. Therefore the analytical view is not suitable. The actors view would imply that the results from the research is dependent of the authors social context and will differ depending on who conducts them, which is not desirable.

3.2 Research method

When conducting a research study it is imperative to decide what research method to use. The method depends on the nature of the study and determines how results will be achieved and how to analyze data.

3.2.1 Quantitative and qualitative data

A quantitative analysis can be conducted on research with numerical outcome and, as Höst et al. argue, quantitative data is often processed through statistical analysis [14]. Quantitative techniques can be used for improved understanding or to show relations and hypotheses. The measures used to explore and describe quantitative data are average value and variance, a measure of deviation. Numerical data can also be described in histograms, box-plots or xy-graphs. The correlation coefficient can then be calculated to explore the relation of two factors, which describes to what the factors correlate.

An important aspect that Höst et al. points out is to investigate if the data contain any incorrect values due to misunderstandings, measurement errors and such [14]. A typical data must be corrected early in the process and can be identified in box-plots or xy-graphs.

In a qualitative method the data to analyze are words and descriptions, and can therefore not be quantified. A quantitative method aims to get a deeper understanding of an area based on a small number of research objects, according to Höst et al. [14]. The data suitable for a qualitative method are text documents, e.g. transcribed interviews or archive material.

Qualitative data collection is a prerequisite to get a deeper understanding of the research object. Hence, the primarily method will be qualitative to understand the current situation, finding out what data to collect and the methods used to collect it at VCE.

As the project proceeds, the method will aim towards a quantitative method when quantitative data is collected. The analysis of collected data will be based on quantitative data. Manual collection of quantitative data is error prone in a wider extent than automated data collection and if such measured data is not correct from the beginning there is subsequently little chance of correcting it afterwards. Hence, manual data need to be collected and documented correctly from the start.

3.3 Data collection

The sources of information in this thesis will be literature studies, interviews and quantitative data. According to Yin there are six sources of information for a study; documents, archival records, interviews, direct observations, participant observations and physical objects [15].

3.3.1 Primary and secondary data

Two traditional techniques for collecting data, according to Arbnor & Bjerke, are collecting new data, so-called primary information and secondary information [13]. Primary data are data directly connected to the conducted study since it has been designed for it. Primary data can be collected through interviews, observations or experiments. Secondary information is previously collected data, which has originally been collected for another purpose. The drawback with secondary data is the trustworthiness since the researchers cannot be sure to what extent the secondary data are correct.

Interviews and collected data will be primary data while literature studies of different manufacturing cost models are secondary due to not being information brought up for this thesis. A large part of the secondary information is articles used to get a deeper understanding of different methods within manufacturing systems.

3.3.2 Interviews

Conducting interviews is a source of background information and can be described as a systematic interrogation of someone on a certain subject. The interview can be conducted by phone or in a direct meeting and the answers can be documented either by hand or by any audio medium. Höst et al. claim that if an interview is a part of a qualitative study the selection does not have a focus on random selection of the polled [14]. Instead, it is important that the selection covers the variation of the population. Therefore, the selection is made by stratification, i.e. the persons to interview are chosen from a number of categories. Since the selection is not random, it is not possible to draw generalized conclusions about the popularity from which the selection has been made. However, it is possible to explore the area quantitatively.

Höst et al. present three different interview structures; unstructured, semi-structured and structured [14]. An unstructured interview is used in an exploring purpose where the discussion is based on an interview guide with question areas instead of clear questions. The risk of this method is that the polled can control the interview by talking more of certain areas, trying to avoid other areas on purpose. To make sure that each area gets enough attention, make sure to dedicate time for each area. An unstructured interview is a qualitative method resulting in descriptive data. Secondly, the semi-structured interview has a mix of question areas and clear questions. The purpose of such method is to get describing or explanatory data. Finally, a structured interview is similar to an oral questionnaire with prepared, clear questions. The advantage, compared to a written questionnaire, is that the polled does not have to fill out the survey themselves and answers can be clarified. The disadvantage is that the survey is more time-consuming to conduct compared to having a written survey.

An interview can be divided in four steps, argue Höst et al. [14]. The first step is to present the context and explain what the purpose of the interview is. The polled should be informed of how the data will be processed. The next step is to ask initiating, simple questions to start the conversation and to get the polled in to the right context. The main questions should then be asked in a logical order. Finally, the interview should be summarized, which gives the polled a chance to add something that seems to be missing.

The first step for this thesis will be to investigate the current situation to get a deeper understanding of how everything works and thus the very first interviews will be unstructured. Subsequently, the interviews will be more structured when having a better understanding of which information is missing. When collecting raw data for manufacturing cost models the surveys will be clearly structured, filled out by the authors and others.

3.3.3 Literature review

A literature study is relevant to improve the knowledge of the authors within the area. It is also important for an independent reader to be able to get insight into the subject and to facilitate understanding of the case concept, analysis and conclusions, argue Höst et al. [14].

The literature review used for this thesis contains terms, models and other tools, which are required to fulfill the purpose of this thesis.

Literature studies rely on secondary information, which imposes a thorough understanding of validity and reliability. Hence, the theoretical framework of this thesis will be based on generally accepted theories and models.

3.4 Credibility

The credibility ensures the trustworthiness of the study and depends on validation and reliability, which is discussed below.

New research is subject for scrutiny; hence, it is in the researcher's interest to ensure trustworthiness of a study. How well the research methodology measures the characteristics that the researcher intends to describe is referred to as validity. According to Yin, there are three different methods to investigate the validity of a study. The methods are construct, internal and external validity. Construct validity is about constructing accurate measures of the investigated theory and avoiding subjective judgments in the data collection. Letting key informants verify the facts or having multiple sources of evidence strengthens the construct validity. Secondly, internal validity concerns causal-effect relationships, e.g. how certain incidents are related. This is a method that only applies to explanatory and causal studies. One tactic to attain internal validation is to conduct pattern-matching, explanation building and time-series analysis. The third method to investigate the validity of a study is to make external validations, which describe to what extent a study can be generalized.

Reliability refers to obtaining reliable results generated by the method used as well as drawing well-underpinned conclusions. It can also be described as to what extent the same results can be obtained when repeating the research. To obtain high reliability the data collection has to be accurately conducted, argue Höst et al. [14].

Validity concerns how well the research methodology reflects reality and will be assured through feedback from the supervisor at the university and at VCE, who has been present throughout the research. To ensure the reliability, sources from peer reviewed scientific journals and literature are chosen. None of the authors of this thesis have worked for Volvo before, which is another factor enhancing the reliability since it decreases the risk of subjectivity.

3.5 The procedure of the study

The first week at VCE was spent on the assembly shop floor with the main purpose to see and understand the processes. Work methods, physical and information flow was observed during this week, which are all factors of importance for understanding the situation at VCE.

Tomasz Maleszka, Manufacturing Manager and supervisor at VCE, introduced a number of persons from the production, quality, logistics and finance departments that would be helpful for the thesis and contribute to a holistic view of VCE. Interviews, unstructured and semi-structured, and meetings were held in order to identify the current situation and the issues within the research area. The literature review has been of great importance from the very beginning. The Internet search engine used for the review was Lovisa, the catalog for Lund

University libraries. The key words used for literature research were; *Manufacturing Cost Deployment, Work Sampling* and *Ratio Delay.*

Information regarding MCD, how it works, what the current state at VCE is and which problems VCE is facing concerning MCD was gained through meetings with both Tomasz Maleszka and Przemek Gorazd, Business Controller at VCE, interviews with persons who works with MCD at Volvo Powertrain, literature review and a company visit to New Holland in Plock, Poland. New Holland in Plock constructs harvesting equipment and the plant has similar processes to the ones at VCE, which is why MCD at New Holland was of interest. MCD has been used there since 2008 and a visit to their factory was a part of benchmarking for the subject.

Research concerning work sampling was conducted by interviews and literature reviews. To get a deeper understanding of the work sampling method, the authors participated in the preparations and execution of the latest round of work sampling at VCE.

4. Manufacturing cost models

This chapter starts by introducing the model called manufacturing cost deployment. The theory behind the model will be presented first, followed by how VCE uses it and an analysis of the current situation and which actions should be taken to improve the performance of the model at VCE. Finally, alternative methods are presented and compared to manufacturing cost deployment and it is described how the alternative method, that could be suitable for VCE, can be implemented.

4.1 Manufacturing cost deployment

There are various manufacturing cost models and manufacturing cost deployment (MCD), developed by Yamashina and Kubo in 2002, is one of them. VCE has conducted two loops of this method but does not achieve significant results to benefit from.

4.1.1 Manufacturing cost deployment

MCD is a methodology that establishes a cost-reduction program scientifically and systematically. The purpose is to use it for a production system with multiple facilities [16]. It is a method to investigate the relationship among cost factors; processes generating costs and various kinds of waste and losses. It also aims to clarify the availability of the know-how of how to get rid of waste and loss. MCD is then used to rank the items for waste and loss according to priority based on cost and benefit analysis. Finally, remedies for improvements are to be identified as well as cost of improvements and expected cost savings. The general idea with MCD is to create six matrices based upon data input concerning waste and losses from a manufacturing company. According to Yamashina & Kubo, MCD solves the following issues:

- Identifying production losses; result and causes
- Finding relations between loss reduction and their possible cost reduction
- Clarifying if the know how on each loss is available, if not it needs to be obtained
- Estimating the cost of reduction

According to Volvo, waste is defined as throwing a bucket of water away for nothing, whilst loss is defined as a leaking tap [17]. Both are non-value adding, but should be separated since they occur for different reasons. Losses can be categorized into c*ausal losses;* loss caused by a problem of a process, equipment or people that can be directly identified, and *resultant loss;* loss such as material, manpower or energy, which are results from causal losses. Typical waste and loss could be within any of the following areas: equipment, material, labor, quality, environment or logistics. The procedure of MCD can be divided into seven steps [16]:

1. Collect data and establish targets for cost reduction.
2. Identify losses, A-matrix.
3. Separate losses into causal and resultant, B-matrix.
4. Translate losses into costs, C-matrix.
5. Identify methods to eliminate losses, D-matrix.
6. Estimate cost for improvement and cost reduction, E-matrix.
7. Establish improvement plan and implement. F-matrix, follow-up.

Yamashina & Kubo exemplifies some losses within three common categories [16]:

Facility:

- Breakdown
- Set up, tool change
- Start up
- Short stoppage
- Speed down
- Defective losses

Operator:

- Management
- Operating motion
- Logistic
- Line organization
- Measurement losses

Material:

- Yield
- Indirect material
- Die and jig
- Energy

The matrices are described in the following sections below [16].

A matrix

The A matrix is the loss-where matrix. It describes which loss appears in what process step and to what extent. The loss types are on the vertical axis and the horizontal axis represents the process steps. The losses are ranked; 1, 2 or 3 where 3 has the highest priority, 2 the second and 1 the third, see Table 4.1 for an example of an A matrix. If a square is empty there is no need for loss reduction.

Table 4.1 exhibits an example of a part of an A matrix [16].

A MATRIX		Storage	Drilling	Turning	Hardening	Cleaning	Packing	Storage
(I) Machine Losses	1. Planned maintenance			1	1			
	2. Breakdown and stop			1	1	1		3
	3. Machine process			1				
	4. Start-up				1			
	5. Changeover			1		1		3
	6. Other downtime		2					
	7. Speed	3				2		
	8. Machine re-work					2		

B matrix

The B matrix, shown in Table 4.2, is used to clarify the cause-effect relationship of identified losses in the A matrix. To reach effective solutions for loss reduction it is important to focus on the causal losses and not the resultant ones.

Table 4.2 exhibits an example of a part of a B matrix [16].

B MATRIX				**Causal losses**							
				Causal machine losses							
				Breakdown and stop			Machine process		Start up	Change over	
				Turning	Hardening	Cleaning	Drilling	Turning	Hardening	Turning	Cleaning
Resultant losses	**Machine losses**	**Break-down**	Storage		X	X					
			Drilling		X	X					
			Turning	X	X	X					
			Hardening	X	X	X					
			Packing	X	X	X					
			Clearing	X	X	X					
			Storage								
		Process	Storage					X			
			Drilling					X			
			Turning					X			
			Hardening					X			
			Packing					X			
			Clearing					X			
			Storage								

C matrix

The losses are converted into costs and then used for C matrix, see Table 4.3. It is used to make the connections between losses and cost visible. There are two types of losses; the time-related loss can be measured in terms of time, such as machine stoppages, and the physical loss that can be measured in terms of quantity, such as number of defectives. The C matrix produces a set of data where the cost type, process step and loss type can be analyzed. The results can be presented in Pareto charts, for instance.

Table 4.3 exhibits an example of a part of a C matrix [16].

C MATRIX

Resultant loss / **Causal loss**				Fixed cost	Variable cost				Total
				Depreciation cost	Direct material cost	...	Cost *k*	...	
Machine	**Breakdown loss**	Process	1	...	...	...	...	...	...
			...	...	...	...	...	...	...
			j	...	...	...	...	...	...
			...	...	...	...	...	...	...
			J	...	...	...	...	...	...
		S		...	...	...	...	...	...
	...			...	...	...	...	...	...
	Loss *l*		j	...	...	...	...	...	...
	...			...	...	...	...	...	...
Total				...	...	...	...	...	...

D matrix

Different losses require different improvement strategies. The D matrix, see Table 4.4, is necessary to consider which improvement techniques that are suitable for each loss. It is also used to identify which KPI´s that will be impacted by each action. Generally, there are two kinds of approaches to choose between when dealing with the losses. The first is the focused improvement approach, which focuses on eliminating waste in the short-term. The second approach is the systematic approach, which requires continuous activities in the long-term [17].

Table 4.4 exhibits an example of a part of a D matrix [17].

D MATRIX

Resultant loss				Individual approach														Systematic approach					
Causal loss				Breakdown analysis	Setup time reduction	Tool life improvement	Start up time reduction	Short stop analysis	PM analysis	Cycle time reductiom	Cp, Cpk improvement	Operation method	Layout improvement	Inspection method	Yield improvement	Material saving method	Energy saving method	Operative maintenance	Preventive maintenance	Predictive maintenance	Quality maintenance	Quality assurance	Education and training
Machine	Breakdown loss	Process	1															X	X	X			X
			⋮																				
			j	X					X									X	X	X			X
			⋮																				
			J	X					X														
			S																				
	⋮																						
	Defective loss	Process	1								X												
			⋮																				
			j								X												
			⋮																		X	X	X
			J								X										X	X	X
			S																				
	⋮																						

E matrix

The E matrix, see Table 4.5, is a project summary which shows the estimated cost of handling and improving the losses as well as the expected cost reduction.

Table 4.5 exhibits an example of a part of an E matrix [17].

E MATRIX

From D matrix																			Benefitting KPI(s) year 1						Benefitting KPI(s) year 2						Benefitting KPI(s) year 3					
Workshop	Project description	Process step	Loss type	Year 0 loss	Team leader	Start date	Planned completion	Duartion [months]	Planned not benefit	Project sponsor	Actual costs to date	Actual net savings to date	Plan. savings year 1	Acutal savings year 1	Plan. savings year 2	Actual savings year 2	Plan. savings year 3	Acutal savings year 3	Cost reduction (plan.)	Cost reduction (actual)	Utilization (plan.)	Utilization (actual)	Yield (plan)	Yield (actual)	Cost reduction (plan.)	Cost reduction (actual)	Utilization (plan.)	Utilization (actual)	Yield (plan.)	Yield (actual)	Cost reduction (plan)	Cost reduction (actual)	Utilization (plan)	Utilization (actual)	Yield (plan)	Yield (actual)
BP	Reduce breakdowns in the cascade section caused by lack of basic conditions	Dryer	Breakdown and stop																																	
BP	Reduce breakdowns in the dryer outfeed caused by a failure to restore	Dryer	Breakdown and stop																																	
BP	Reduce breakdowns at the bundler caused by human error	Trim and tape	Breakdown and stop																																	
⋮	⋮	⋮	⋮																																	

F matrix

The F matrix is used as a planning tool to make sure that the chosen projects will be implemented and that the resources are well balanced [17]. Table 4.6 shows an example of what an F matrix could look like.

Table 4.6 exhibits an example of a part of a F matrix [17].

F MATRIX									1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Workshop	Process step	Loss type	Project description	Project no.	Project leader	Planned savings	Planned costs	Project resources (man-hours)	23/01/2007	05/02/2007	14/02/2007	06/03/2007	21/03/2007	06/04/2007	25/04/2007	18/05/2007	21/05/2007	07/06/2007	24/06/2007	05/07/2007	15/08/2007	31/08/2007	09/09/2007	22/09/2007	10/10/2007	31/10/2007	06/11/2007	26/11/2007	08/12/2007	15/12/2007	03/01/2008	10/01/2008
Ongoing projects																																
BP	Mixer	Breakdown	Mixer area	2	TO						Step 0			Step 1							Step 2				Step 3							
BP	Forming	Process downtime	AM: Forming belt transfer	3	FG									Step 0		Step 1					Step 2					Step 3						
BP	Dunnage machine	Line organisation	Reduce breakdowns	4	MO														Step 0		Step 1				Step 2		Step 3					
E matrix projects																																
BP	Packing	Material process	AMFI: Take off part 1	5																				Step 0		Step 1		Step 2			Step 3	
BP	Packing	Material process	AMFI: Take off part 2	6																					Step 0			Step 1				

4.1.2 Current situation and identified gaps

MCD is a relatively new method, which has been implemented at VCE two years ago. The method is also used at Volvo Powertrain, where it was implemented successfully together with Yamashina, according to Gorazd [18]. The concept has been copied to VCE and during the two previous years the method has been conducted twice, but it is still not used with confidence. Today it is more of an administrative task than a method for evaluating and improving the performance at VCE since there has been no result in terms of action.

The matrix-templates used at VCE origins from Volvo Powertrain but have been modified in an attempt to make them suitable for the plant. One size does not fit all and the same applies for the MCD matrices. The foundation for MCD is six matrices, which are explained in section 4.1.1, but VCE only uses the first matrices: A, B and C. The last steps of MCD have been treated during meetings but there were no official results in terms of cost reduction, claims Gorazd [18]. He also claims that the analysis of MCD confirmed what was already known about where losses occur.

There is a lack of dedication of using MCD since the project responsible for MCD does not believe in the concept. As mentioned above it is more of an administrative task, something that should be done independent of its contributions, and without results it becomes a loss in itself, a non-value adding activity. One of the keys for a successful MCD, and this is true for successful implementation of any method, is to make sure that the personnel involved are devoted.

The purpose of the A matrix is to show losses and where they occur. Since the processes are divided among many stations in the assembly, the processes in their matrix have been divided into assembly areas such as main line, sub assembly, cab assembly and a few work areas. These areas contain many stations and thus it is hard to identify the area in which the root cause occurred. The B matrix is to be based on the previous matrix and is complex to gather input for since it is supposed to reflect how losses in processes affect losses in other processes. This reflection is missing in VCE's matrix, which simply connects a resultant loss with a causal loss and does not include the affection of losses on other processes. The C matrix is supposed to be based on the B matrix, but since this matrix is not correctly made it results in an incorrect C matrix. In fact, the A and C matrices are almost identical. The major differences is that the output for the A matrix are losses, ranked 1, 2 or 3, and the output for the C matrix are costs of the losses. Also, there are more process steps in the A matrix than in the C matrix. Equipment breakdown, waiting and line balancing are shown on the y-axis when in fact waiting is a loss that can occur when the line is poorly balanced or when equipment breakdown causes a stop of the line. If no account is taken of this it leads to double counting for some of the losses, which is currently the case.

VCE bases one loop of MCD on data from three months. Three departments at VCE are contributing with input for the matrices; quality, logistics and assembly. Each department is responsible to fill in the cost for the losses concerning them. There are no standards of how to calculate the different costs to ensure the validity of the results or to be able to compare them from year to year. For instance, when calculating the cost of transport during the current period, there are different ways of doing it. The information of how much time is spent on transportation is available as a percentage of the total time of direct work. One workday is eight hours, 480 minutes, and planned breaks and meetings are 47 minutes a day, which means that the actual direct time spent on work corresponds to 433 minutes a day. During the latest loop the transport time was based on a workday of 433 minutes while the loop before based the transport time on a workday of 480 minutes. Should the transport time be based on the whole workday, the expected direct work in the production or should stop lines, kaizen, extra meetings etc. also be taken into account? If a standard is not set, there is a risk of calculating the losses differently and a comparison between results from two different loops will not say much about the potential improvements made and in the end there will be double counting, i.e. losses will be been represented not once but twice.

The factory at VCE includes few manufacturing operations, most operations are assembly and they are made manually. Hence, the level of automation is low and data input for MCD has to be gathered manually as well. Raw data input collection is made with a method called work sampling, see chapter 5.

4.1.3 Improvement possibilities

The first step to improve the work with MCD at VCE is to convince the management team about the importance of using MCD and what the benefits of using it implies. The team involved needs to be fully devoted to the method and believe that it can make a change. Unless the management is not one hundred percent committed to the method, VCE will never get the benefits of using MCD and it will continue to be a time-consuming method causing more losses than it will contribute to reduce. In the beginning it will require both effort and time to fully implement MCD but when that is done, when the concept for data collection is well-functioning and when improvements are starting to show, MCD will run smoother and most importantly; seeing results in terms of saved costs will keep up motivation for continuing.

All parties involved in MCD should have the understanding of how the method works, why it is used and the benefits of it. As recommended in the next chapter about work sampling, it is essential that also team leaders and operators are convinced about the advantages with MCD to keep up motivation for gathering data and later on to implement improvements. The advantage of having the team leaders conducting the samplings is that they are highly knowledgeable in the operations and if they become trained in the general lean thinking of value and non-value adding activities, the team leaders can become an even more useful resource in the work for improvements.

At the moment, there are no expectations of achieving results from MCD. If there is no pressure or obligation to achieve results there will be no motivation to strive for completing the D, E and F matrices – which is where the real work and effort for results are starting to show.

Additionally, when working with improvements there has to be a good set of tools to find the right remedy for each loss.

The resultant losses in the matrices are divided into large process groups such as main line, sub- and cab assembly. Having such broad categories makes it hard to locate where the losses occur. Since the assembly is divided by stations and work areas, where one work area consists of several stations, one solution is to use one of these categories instead of actual processes in the matrices. When applying work sampling as input for MCD, an extensive amount of work is required to gather raw data for each station compared to the workload of data collection for each work area. This is because there are more stations than work areas, and sampling each station would therefore require an extensively larger number of observations to reach a high reliability of results. Therefore, it is recommended to put the work areas as process categories instead of main line and sub assemblies.

Resultant losses in the matrices are sometimes treated as causal losses in VCE's matrices, which results in the root causes of the losses not being identified. Causal losses need to be well defined and distinguished from the resultant losses to create prerequisites for finding a solution.

To make it easy to follow and understand the matrices it is essential to include explaining comments in them; it is better having too many than too few. Also, the comments need to be easy to find and read. If comments are far away from what is commented there is a risk that they will not be used at all. The comments will make it easy to go back and see what has been done and why. The user-friendlier a method is, the easier it is to keep the parties involved motivated. If there is little motivation to use the method there is a risk of having data inputs of uncertain quality and results thereafter. Objectives need to be set to have a goal to strive for, e.g. identify 30 % of the costs as losses and reduce the losses with five percent.

Standards of how to calculate costs in the C matrix should be set to ensure the validity of the results. This will also enable the comparison and evaluation of results from earlier loops of MCD. Double counting of causal losses in the matrices creates a false image of reality and should consequently be avoided. As the example with calculating transport time, mentioned in section 4.1.2, transport for instance can be based on 433 minutes per workday excluding time for Kaizen, QPRS, line stoppages etc. where transport is not performed. This would imply a better value for the cost of transportation in the C-matrix. If the time for Kaizen, QPRS and line stoppages are not excluded, it will indicate that more time is spent on transportation than it is in reality. Concurrently, the time for kaizen, QPRS and line stoppages is counted as losses, but under other categories, which implies double counting.

The A matrix is currently, and originally, using a scale of 1, 2 and 3 to prioritize losses. This implies that three losses with the lowest priority will be as important as a loss having the highest priority, which could create misleading results. To separate the losses better, one recommendation is to rate losses with 1, 3 and 5 instead, which means that losses of the highest priority will also be highlighted the most. Also, there cannot be too many losses having the highest priority, which means that there will have to be a priority within the highest prioritized losses. According to Lundgren [19], a goal is not to have more than 10 % losses with the highest priority. This is to be able to focus and not loosing grip because of handling too many losses at the same time.

Each and every loss identified in the A matrix should be investigated to document the affection of each loss on other processes. This is to increase the understanding of the processes, but primarily to calculate the real cost of the loss. Since the B matrix is based on the A matrix and the C matrix is to be based on the B matrix, they become incorrect. A prerequisite before starting to make shortcuts in the method is to know, understand and have experience in the methodology.

When it comes to remedies of losses there is a need for great transparency. If one loss has been remedied it could affect another loss and result in having moved loss from one category to another. Also, if transport decreases on some stations but not on stations with the highest cycle times, this will only imply more waiting which is why it is important to rebalance the stations to gain full benefits. Thus, loss relations need to be identified in the matrices.

MCD should not be seen as something additional to the already established methods for improvement work at VCE or an administrative task made for the VPS academy. It should be a regular part of the improvement work just as kaizen and 5S are for continuity and proceeding work for improved results. Therefore, it is also important that the methods for collecting the data will be well established and systematic. MCD cannot be a method used only once; firstly, because it is hard to get good results from the first loop and secondly, because there are no previous results to compare the results to, which is a necessity to measure the progress. Also, as improvements are achieved, new problems will arise with needs for new improvements. After several loops of MCD the enhancements of using it can be identified and it is not until a number of loops has been completed that MCD can be fully mastered.

The matrices for MCD will eventually grow quite big, in fact both matrix A and C are quite inconvenient to look at on the computer screen. During the visit at New Holland the visual advantages of having the matrices printed on the walls was discovered. The matrices become more transparent and visualized compared to having them on a screen to be seen one by one.

4.2 Alternative manufacturing cost models

MCD is a comprehensive manufacturing cost model but it is not the only one. This section aims to investigate whether there is another manufacturing cost model that would suit VCE in their strive to reduce costs. A comparison between MCD and the alternative methods is done to see how it differs from other models, to visualize pros and cons with each method, within which aspects they are similar and in which they differ.

Through the years many different manufacturing cost models have been developed to evaluate production processes. Some models are more similar than others, some focus on specific problems and some are more general. Jönsson [2] presents twelve different models, including MCD. Table 4.7 summaries the models he presented and the corresponding parameters. The models chosen for the comparison with the MCD are the ones including the highest number of parameters, since it is desirable to get the most holistic view possible. The model developed by Ståhl [20] is one of the twelve models, but it is not presented in the table. Since it includes the majority of the parameters, according to Jönsson, it will be a part of the comparison. Two models wills be compared to MCD, and the model developed by Son [21] is the second model that is chosen for the comparison.

Both the model developed by Özbayrak et al. and the one developed by Chiadamrong include the greater part of the parameters. The model by Özbayrak [22] is an activity-based costing model where a third of the included parameters in Table 4.7 are not included as separate parameters, why it will not be included in the comparison. The model developed by Chiadamrong is similar to the one developed by Son, but does not include as many parameters and has a heavy focus on quality [23]. Because of the similarity and Son's wider perspective, the model by Chiadamrong is not included in the comparison.

Tabell 4.7 exhibits different manufacturing models and which parameters they include [2].

	Koltai et al. [67]	Özbayrak et al. [68]	Aderoba [69]	Dhavale [70]	Yamashina and Kubo [75]	Son [76]	Chiadamrong [77]	Cauchick-Miguel and Coppini [71]	Branker et al. [78]	Noto La Diega et al. [72]	Needy et al. [74]
Material		x		x	x	x	x	x	x		
Labor		x	x	x[1]	x	x	x	x	x		x
Machine depreciation	x[1]	x[1]	x	x	x	x		x	x[1]	x[1]	x[3]
Floor space		x[1]	x	x		x		x			
Utilities (e.g., energy)		x[1]	x	x[1]	x	x	x	x[1]	x		
Tools	x	x	x[1]	x[1]	x	x		x	x	x	
Maintenance	x[1]	x[1]	x[1]	x[1]	x	x	x	x[1]	x[1]		
Repairs			x[1]			x	x[1]				
Material handling	x	x		x[1]			x		x	x[1]	x
Computer		x[1]		x[1]		x			x[1]	x[1]	
Inventory	x	x		x[1]		x					
Quality: prevention							x[2]				
Quality: appraisal	x[1]				x	x	x	x			
Quality: failure (scrap)		x[2]			x	x	x				
Reworking		x[2]				x	x	x[1]			
Downtime		x[2]			x		x[1]				
Speed loss					x						
Set up	x	x			x	x	x	x	x		x
Waiting		x	x[1]			x	x				
Idling						x	x			x	
Environmental									x		

[1] Included but not as a separate parameter.

[2] Mentioned as considered, but the equation is not presented in the paper.

[3] The cost is expressed as a leasing cost.

4.2.1 Manufacturing cost model by Son

Son has developed a manufacturing cost model that serves as support for strategic decision-making for factory automation and has developed the integrated manufacturing performance measure (IMPM), which is based on this model. Son argues that productivity, quality and flexibility are both the most critical components of manufacturing strategy and the most critical measures of performance of manufacturing systems, which is why these components should be quantifiable and transformed to financial terms. The purpose of the article, where the method is provided, is to *"..identify cost elements which should be included in the analysis of advanced manufacturing systems and propose a way of estimating them. Also discussed are various approaches to obtain parametric values of the cost model and applications to performance evaluation and project justification"* [24].

Productivity, quality and flexibility are three groups in which Son divides costs. The productivity group includes costs of labor, material, depreciation, machine, tool, floor space and computer software. The quality group includes prevention and failure. Flexibility, which is the last group, includes set up, waiting, idle and inventory [21]. The three groups are regrouped into two new groups; relatively well-structured costs and relatively ill-structured costs. Since the productivity costs is actual, concrete input required for manufacturing of products they are included in the relatively well-structured costs. Quality costs and flexibility costs are included in the relatively ill-structured costs because of two main reasons; lack of knowledge and unwillingness to explore the problem in depth [21].

Son's model is used to calculate the total of each type of cost during a predetermined period. Below the equations for calculating each cost are presented.

The labor cost, C_L, is defined as [21]:

$$C_L = direct\ labor\ cost + indirect\ labor\ cost + fringes \qquad 4.1$$

The material cost, C_R, is the cost of making the material ready for manufacturing, such as direct material, ordering, purchasing, transportation and lubricants. The material cost is defined as [21]:

$$C_R = direct\ material\ cost + indirect\ material\ cost + ordering\ cost \qquad 4.2$$

The machine cost, C_M, is defined as [21]:

$$C_M = utility\ cost + maintenance\ cost +$$

$$repair\ cost + insurance\ cost + property\ tax \qquad 4.3$$

The tool change costs is not included in the tool cost since if the change is made manually it is included in the labor cost and the automatically tool changes are negligible. The tool cost, C_T, is defined as:

$$C_T = unit\ cost\ per\ tool * total\ number\ of\ tool\ changed \qquad 4.4$$

The floor space cost, C_S, is defined as [21]:

$$C_s = space\ cost\ per\ square\ foot \cdot manufacturing\ floor\ space \qquad 4.5$$

The computer software cost, C_C, is the cost of maintaining computer software and does not include costs such as salaries of programmers and operators, maintenance, repair, insurance and space cost for computer facilities since they are already included in other costs. The computer software cost is defined as [21]:

$$C_C = licensing\ cost \cdot number\ of\ licenses \qquad 4.6$$

Son has not defined the depreciation cost; instead he is referring to the accounting records where it usually is available.

The prevention cost, C_P, is defined as the cost of preventing defective finished products. The prevention actions can be checking and correcting quality problems. The costs of sampling, assignable cause and process capacity are included in the prevention cost per hour. The prevention cost for a specific product in a specific machine is defined as [2]:

$$C_P = prevention\ cost\ per\ hour \cdot planning\ horizon \tag{4.7}$$

The failure cost, C_F, is the cost that occurs when the finished products do not meet quality standards set by both the company and the customers. It includes the cost of reworking a good part because of misclassification, reworking a defective part, scrapping and dissatisfying a customer by selling a defective part [21]. The failure cost of specific part is defined as [2]:

$$C_F = failure\ cost\ of\ part \cdot quantity\ of\ parts\ produced \tag{4.8}$$

The set up cost, A, is the cost of getting the machines ready for each production run. The set up cost for a specific machine is defined as [2]:

$$A = set\ up\ cost\ per\ unit\ time \cdot total\ set\ up\ time \tag{4.9}$$

The waiting cost, C_W, is the cost of work-in-process inventory and is defined as [21]:

$$C_W = waiting\ cost\ per\ unit\ time \cdot total\ waiting\ of\ parts\ produced \tag{4.10}$$

The cost for under-utilization of manufacturing equipment is the idle cost, C_I, which is defined as [21]:

$$C_I = idle\ cost\ per\ unit\ time \cdot total\ setup\ time \tag{4.11}$$

The inventory cost, C_H, only includes the inventory costs for raw material and finished goods and is defined as [21]:

$$C_H = warehouse\ space\ cost + holding\ cost + shortage\ cost \tag{4.12}$$

The IMPM measures manufacturing ''effectiveness'' and remedies the productivity paradox [21]. The productivity paradox indicates that a high productivity does not necessarily result in higher profitability. The efficiency of transforming tangible inputs into output is a productivity measurement. It is not affected of the ability of the manufacturing system to adapt to customers' whim or products that have not been sold due to poor quality. The IMPM takes the productivity cost, quality and flexibility cost into account.

$$IMPM = \frac{total\ \ output\ value}{productivity\ cost + quality\ cost + flexibility\ cost} \tag{4.13}$$

4.2.2 Systematic production analysis

Ståhl provides a manufacturing cost model called the systematic production analysis (SPA), which includes a production performance matrix (PPM) [20]. The purpose of the method is *"to set the foundation for changes and development for a production system... to identify the loss terms of quality, downtime and production rate"* [25]. The matrix is built up by resultants and causes for the resultant losses. Ståhl also presents a cost relation to turn output into costs when prioritizing losses, but output can also be presented in time or frequency.

The total efficiency, equation 4.14, is a measure based on the loss terms; quality, downtime and production rate. The parameters are explained in Table 4.8. The Lean-triangle in Figure 4.1 illustrates the priority of effort between the loss terms when using total efficiency as the objective function. The first priority should be to eliminate quality deficiencies, q_Q, after which downtime, q_D, and rate losses, q_P, should be addressed. According to Ståhl, solving capacity problems by increasing production rate or investing in additional equipment or automation when having problems with the losses will only increase them [20]. After eliminating quality problems and downtime the final step can be approached; increasing the production rate. To avoid increasing quality disruptions or downtime it is required to undergo technical development and improved competencies.

Table 4.8 exhibits the parameters for total efficiency.

q_Q	Share of quality loss (-)	**N_0**	Nominal batch size (number of units)
q_D	Share of downtime (-)	**t_P**	Real production time (h)
q_P	Share of production rate loss (-)	**t_0**	Nominal cycle time per item, including downtime, but excluding rate loss (h)
N	Real batch size (number of units)	**t_{0v}**	Real cycle time, including rate loss, but excluding downtime (h)

$$Total\ efficiency = \left(1 - q_Q\right)^3 \cdot (1 - q_D)^2 \cdot (1 - q_P) \tag{4.14}$$

$$q_Q \ = \frac{N - N_0}{N} \tag{4.15}$$

$$q_D \ = \frac{t_P - t_0}{t_P} \tag{4.16}$$

$$q_P \ = \frac{t_{0v} - t_0}{t_{0v}} \tag{4.17}$$

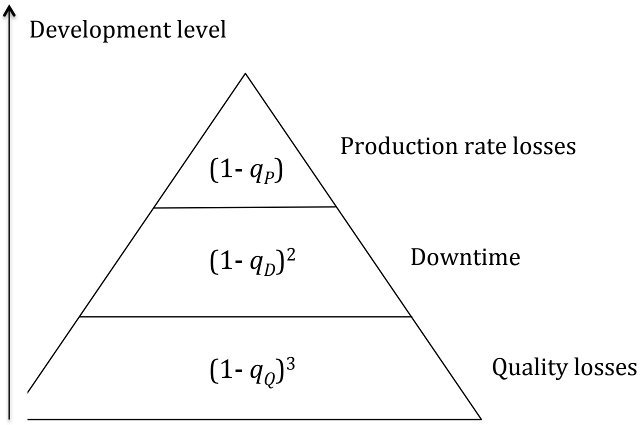


Figure 4.1 exhibits the Lean-triangle, which illustrates the priority between the different loss terms [20].

Environment and lifecycle issues are other important aspects in addition to the result parameters presented in accordance with the Lean-triangle since it contributes with an important perspective in the assessment of production results and its effects. The result parameters; quality, downtime, production rate and environment, combined with several factor groups constitute the foundation of the PPM. A template for the matrix can be seen in Table 4.9, where horizontal summery gives the cost for a given factor and vertical summery gives the cost for a given result parameter. The factors are the causes of the result parameters. Briefly, a PPM is used to study the relation between disturbances and the cause of them with a structured method. The PPM can be analyzed in three ways; the same matrix is used, but numbers can be translated into frequency, time or cost. Independent of what analysis is chosen the most critical result parameters and their respective factor groups must be identified to undergo improvements first. SPA and its PPM is primarily used in manufacturing industry and has several purposes:

- Follow up ongoing production to find opportunities of improvement.
- Constitute the foundation for constructing future production systems.
- Assessment of result and factor parameters can help when making decisions regarding work material, tools and machinery equipment.
- Documentation of experiences and competencies.

The factor groups in the PPM consist of many individual factors, which can be divided into more detailed categories:

- *Tools* – geometrical, surface and material related factors.
- *Work material* – geometric, surface and material related factors.
- *Process* – equipment related factors, process data and additives and other preparation related factors for the refining process.
- *Personnel and organization* – instructions, action plans, routines, administration responsibilities etc.
- *Wear and maintenance* – tool related factors, planned and unplanned maintenance.
- *Special factors* – unique process characteristics.
- *Peripheral equipment* – material handling equipment, conveyers etc.
- *Unknown factors* – a category used not to mix anything in the other factor groups that do not belong there - that would affect the quality of their results. The number of registers under this category highlights the needs for a general competence development.

Table 4.9 exhibits the principal structure of a production performance matrix [20].

	Result parameters				
Factor groups	Quality parameters	Downtime parameters	Production rate parameters	Environment and lifecycle parameters	**∑ Factors**
A. Tools					
B. Work material					
C. Process					
D. Personnel and organization					
E. Wear and maintenance					
F. Special factors					
G. Pheripherical equipment					
H. Unknown factors					
∑ Result parameters					

Successful production development leads to releasing production capacity in the current production system. To assimilating the results of this development the workload needs to increase, else overcapacity increases and utilization decreases. Overcapacity can be used as a reserve for increased demand, if it is possible to increase by market shares. If there is no forecasting of increased demand or other plans for assimilation of the increased capacity the development could cause closure of the production unit due to collocation with similar production units or the overcapacity will have been an investment with no return.

4.2.2.1 Data collection for a production performance matrix

SPA has had greatest impact when being used as a foundation for continuous improvement within critical production sections, according to Ståhl [20]. He provides the following steps when applying SPA for production improvements:

1. Identify the result parameters and requirements critical for the function of the part, which will be the parameters for calculating the quality parameters, q_Q. The downtime parameters, q_S, are identified by disturbances causing downtime. Intended production rate needs to be identified to note rate losses, which are represented in the production rate parameters. Consumption of supplies, process additives etc. are identified as environment and recycle parameters.
2. Identify impacting factors for every factor group.
3. Identify potential relations between result parameters and factors.
4. Identify and prioritize relations between result parameters and factors.
5. Register the events connected to the result parameters to find the underlying factors.
6. Analyze the collected data.
7. Construct an action plan to optimize and change the production, based on the outcome of the analysis.
8. Implement the action plan.
9. Follow up and evaluate the implemented actions.

4.2.2.2 Constructing the production performance matrix

The introductory task when constructing a PPM is to identify the result parameters. The quality parameters for instance should be based on the reasons for why a part is scraped, e.g. wrong dimension, surface or property, argues Ståhl [20]. When setting the result parameters it is the reason for why an item is scraped, not why the error arose, that needs to be identified.

Downtime parameters can be divided into two main groups: planned and unplanned. Also, downtime due to changeover, which belongs to the category of planned downtime, should be reported separately.

The production rate parameter should be based on the decreased rate due to shortage of staff, testing, leakage etc. Sometimes it is suitable to have different levels of rate loss, i.e. 25 % of intended production rate.

Environment and lifecycle parameters are sometimes hard to find and to measure. Examples of parameters within the category are cutting fluid, energy consumption and scrap material.

When calculating costs for the PPM in terms of material, downtime and wage, the following cost relation, calculating the production cost per item, can be used. The cost relation should be calculated for each production process step where the losses q_Q, q_D and q_P can be identified.

4.2.3 Comparison

MCD and SPA both express a clear aim of striving for development and also consider loss as an improvement opportunity. The purpose of Son's model does not discuss improvement opportunities or reducing costs. In general, one way of reducing costs is to reduce and eliminate waste and losses, but neither are there suggestions of doing so in the model by Son, compared to the purposes of MCD and SPA. The focus of Son's model lies more in the evaluation of whether or not the productivity is profitable using IMPM, which is an important aspect, but is outside the frame of cost reduction.

What MCD and SPA also consider is the cause-resultant relationship between the losses, while Son focuses on large and general cost items. With Son's model, it can easily happen that the various cost items are compared with each other, but that will not tell where the actual waste and losses are since the causes of the costs are not identified, as with MCD and SPA. For instance, if the result for Son's model is that material cost is the highest cost it does not necessarily imply that material cost has the greatest prerequisites for cost reduction, compared to other cost items.

When using MCD, there can be as many or as few losses or wastes as is desirable to investigate, while Son has a fix set of cost items for evaluation. Its costs include many factors and finding the root causes for the cost becomes difficult. The model by Son can thus be seen as a more shallow method than the other two, since it does not seek to identify the cause-resultant relationship. The costs within MCD and SPA though are clearly connected to the root causes. Consequently, waste and losses can be identified and then eliminated or improved. It can be concluded that Sons model does not focus on eliminating waste and losses, as for MCD and SPA. Instead, Sons model should be used to evaluate cost items over time, e.g. to compare material cost from year to year to see the development of cost items.

MCD focuses on reducing waste and losses and enhancing processes using a holistic view, while SPA focuses primarily on correcting deviations, e.g. scrapped parts and unplanned downtime, and the secondary focus is to evaluate planned downtime such as set up and tool change. Eliminating scrapped parts and downtime implies releasing production capacity, which can be used in many ways. The priority within SPA of primarily making the current processes do what they are supposed to and secondly attacking the process to enhance it, is logical in theory while in reality it may seem easier to invest in more resources and equipment to make up for the malfunctioning ones. This aspect is not discussed in MCD, where the provided approach is to start where the areas identified have the biggest waste and losses, according to the assessors. MCD suggests no clear method for how these areas would be identified more than from estimations and analysis through occurrence frequency. A disadvantage of MCD is that it does not take the total manufacturing cost into consideration, only the costs of losses. Ståhl takes this into consideration in the cost relation while Son's method is based on calculating the costs for the different parts of a manufacturing plant.

MCD is an entire concept of how to identify waste and losses, which improvement actions should be taken and how to implement them in a structured way. The benefit is that if all matrices are used there will be a plan for how to proceed after identifying where the big losses occur. Improvement actions are visualized by the matrices, as well as by the expected savings from the actions. Drawbacks are, as for VCE, that when starting with MCD there could be too many wastes and losses identified and the motivation for continuing with the rest of the matrices risks to decrease, matrix by matrix. MCD is the method that encourages the cost evaluation to result in actual cost savings by making remedies a clear step in the cost reduction process. SPA includes the remedies as a part of a number of steps to follow, where creating a PPM is one of the steps.

Son discusses strategic decision-making about factory automation, but as Ståhl argues, it is important to first have accurate processes with high utilization of the resources at hand, before making further investments in resources [20]. If there is no plan for how to use the released capacity the investment is a waste since it will not pay off if the additional capacity is not used. This fact is not mentioned in MCD, but then there can be improvements without reducing costs and as long as it contributes to general improvements, and not just for a specific function or operator, it can be good enough by itself. MCD highlights the investment cost in relation to the cost reduction, which should be considered being a self-evident aspect, but is not discussed in either SPA or Son's model.

Investing in new resources or automation requires high utilization of the available resources, as Ståhl argues, and MCD does not specifically treat this issue. Not only should waste and losses be cut, but also unnecessary costs should be prevented from arising by efficient use of equipment and resources at hand. Son discusses a similar topic; the integrated manufacturing performance measure (IMPM), measuring the productivity in contrast to sales, i.e. whether or not the company makes money from the output. If this measure is negative it does not matter how efficient manufacturing is, profitability will not increase with efficient manufacturing if sales does not increase.

The matrices in the MCD and in SPA help visualize the results and it is easy to get an overview of the problem areas. Son's model also visualizes the different cost items, but the causes for them are not part of the resulting cost matrix. MCD is especially systematic with its matrices compared to both SPA and Son's model and having matrices with clear purposes helps the user in the right direction and helps the user to focus on what is important. An advantage with the PPM is that there is a clear structure to start working with from the beginning, which can be further developed, whereas the categories need to be identified with MCD.

A drawback with both MCD and the model by Son is that neither of them considers the cycle time, something that the SPA does. The cycle time is a parameter that is used everyday and is easy to understand. Deviations from the nominal cycle time indicate errors in the production process.

SPA is the only method taking the cumulated effect of material cost into consideration. The material cost for every production process step is calculated. Hence, it becomes evident that scrapped parts in a later process step will result in higher costs than in an earlier step. This fact is an important aspect that makes it easy to know where to start eliminating waste.

Logistics is suggested to be part of MCD and some logistics is included in Son's model, but it is not included in SPA since the main focus is identifying and eliminating deviations from the actual manufacturing processes. Of course, it is fully possible to add logistics on own terms.

To summarize the differences between the three models a table has been created to visualize them, see Table 4.10. Each of the models has their benefits. Son presents a method to compare and evaluate cost items in a holistic view, but has little focus on the root causes of the costs and how to achieve improvements. MCD is a structured concept of how to identify waste and losses by considering improvement actions and implementation of them using a holistic view. A drawback with both MCD and Son's model is that cumulated material cost is not taken into consideration. This aspect highlights the importance to decrease scrapped items due to errors in operations at the end of a manufacturing process. An advantage with MCD is the consideration of cost savings and the return of investments. The focus of SPA lies in eliminating deviations and strives for using current equipment and resources efficiently, which is an important aspect when capacity appears to be scarce. The importance of having a plan for released capacity is highlighted and it becomes evident that development resulting in decreased utilization is a waste of investment if the released capacity is not used. Furthermore, it is a user-friendly method that is simple to use and understand. Also, it includes the cycle time and cumulated material cost, which neither of the other two models does.

Table 4.10 exhibits a summary of the comparison between the three manufacturing cost models.

	MCD	Son	SPA
Focus	Eliminate waste and losses in manufacturing processes	Visualizes costs items for maufacturing processes	Eliminate deviations in manufacturing processes
Cause-resultant relationship	Visualized in matrix B	Not considered	Visualized in the PPM
Waste and losses	Identified in matrix A	Not identified	Identified in the PPM
Total profitability	Not included	In the IMPM	Not included
Approach	Clear and easy to follow due to the matrices	Includes no approach in particular	Has an eight step methodology
Utilization	Does not include such details	Consideres the utilization of equipment	Calculates it and emphasizes the importance of using released capacity instead of just decreasing utilization
Cumulated material cost	Not included	Not included	Material costs cumulate as parts are processed, calculated with the cost relation
Total manufacturing cost	Not included	Is calculated but divided into item costs	Is considered using the cost relation
Cycle time	Not included	Not included	Is considered in the cost relation when calculating manufacturing cost

4.2.4 Choice of alternative model

VCE is not a typical manufacturing production and it is difficult to apply the manufacturing cost models. Primarily since the majority of the activities are manual assembly consisting of variable operations instead of standardized work processes. For the same reason it is hard to collect data input.

SPA is a suitable manufacturing cost model for VCE since it is has a strong improvement focus, which is important for VCE, it has a clear course of action, it considers the cause-resultant relationship between losses, it is user-friendly and considers also the total manufacturing cost. Son's model is applicable on VCE but since there is no focus on the root causes of the costs and where they occur the SPA is a better option.

4.2.5 Analysis of a potential implementation of SPA at VCE

A PPM could be created for the entire shop floor, but to get closer to the problems VCE is recommended to make PPMs on the individual stations. Making PPMs on the individual stations makes it easier to find the root causes and to find solutions to those root causes. If it is desirable to get an general overview of the whole production the PPMs for each station can be summed together and form a PPM for the entire shop floor.

Since there are several stations in the assembly the recommendation is to start doing PPMs for the most problematic stations. A proposal for how the PPM can be created is presented in Table 4.11. The data unit to document can for a start be time since it, more or less, correlates to cost. Later on, when being familiar with SPA, the unit can be translated into costs, but this is more complicated and it is better to focus on learning and conducting the method correctly before making it more complicated.

Table 4.11 exhibits a PPM developed for VCE.

	Result parameters								
	Quality parameters		**Downtime parameters**				**Environment and lifecycle**		
Factor groups	Scrap	Rework	Planned downtime	Unplanned downtime	Planned maintenance	Unplanned maintenance	Packing	Energy	**∑ Factors**
A. Tools									
- Screw driver									
B. Work material									
- Lack of material									
- Defected material									
- Dimension error									
C. Process									
- Documentation									
D. Personnel and organization									
- Incorrect assembly									
- QPRS									
- Kaizen									
- Meetings									
E. Wear and maintenance									
F. Special factors									
G. Pheripherical equipment									
- Conveyer									
- Cranes									
H. Unknown factors									
∑ Result parameters									

As can be seen in Table 4.11 the production rate is excluded among the result parameters. This is because it is hard to consider the production rate at VCE since it is mostly assembly and to avoid different interpretations. The extra time it took to perform an operation can as well be counted as downtime as lower production rate. It is important to be consequent and therefore the production rate is excluded to avoid some people filling in production rate and others downtime for the same factors.

The most optimal is if the operators by them self can collect the data for the PPM, why it is important to educate both team leaders and operators in SPA. Every occurring deviation should be documented on a template telling the time it occurred and the time consumption of the error and explaining what the error was. Data is then to be forwarded into the PPM for the corresponding station and put under the correct factor group and resultant loss. For instance if there is trouble with a cranes and it takes 15 minutes before the operator can continue his work, 15 minutes should be added to the box under *Cranes* (factor group G) and *Unplanned downtime.* It is not always realistic to document every error that occurs since some of them might only consume little time relative to the cycle time. A lower boundary for which errors to be documented could be beneficial.

The amount of time spent on kaizen is recommended to be a part of the SPA to easily document the time-consumption for this activity. The number of personnel present for the activity from the station should be multiplied with the time spent on conducting a kaizen.

There is no standard duration of data collection for PSM, it depends on the downtime (DT). Generally the time before a failure (TBF) period can be linked to the subsequent DT period. One problem that can arise when processing the collected data is how to treat the time before the first DT and after the last DT during several measurement periods, e.g. before and after breaks. A good way to do it is to add all periods so that the time after the last DT in the first period is added to the time before the first DT in the second period. Since the TBF period can be linked to the subsequent DT period it is possible to calculate key ratios for each cycle of TBF/DT. For instance the DT ratio, q_{si}, can be defined as [20]:

$$q_{Si} = \frac{DT_i}{DT_i + TBF_i} \qquad 4.18$$

The total amount of time for collecting data can be determined through a number of cycles, k=i, of TBF/DT. The total amount of q_s is defined as:

$$q_S(k) = \frac{\sum_{i=1}^{k} DT_i}{\sum_{i=1}^{k} DT_i + \sum_{i=1}^{k} TBF_i} \qquad 4.19$$

A rule of thumb is that when q_{Smean}, $q_s(k)/k$, is stabilized it is enough measurements made.

To achieve a stable value of q_{Smean} and to get representative data for analysis of the production, the shortest amount of time, T_k, required to collect data can be estimated as [20]:

$$n_c(MTBF + MDT) < T_k$$

$$30 < n_c < 60 \qquad 4.20$$

where n_c is the number of cycles, MBTF is the mean time between failure and MDT is the mean downtime.

MDT is defined as [20]:

$$MDT = \frac{\sum DT}{k} \qquad 4.21$$

where k is the number of stops during the measured period. MTBF is defined as [20]:

$$MTBF = \frac{t_{tot}}{k} - MDT \qquad 4.22$$

where t_{tot} is the total time of the measured period.

It is important to do the calculations for the amount of time required to collect data otherwise there is a risk of PPM becoming inaccurate and a poor base for further investigations. If the data is properly collected during an enough amount of time and it is filled in the PPM there will be a good base for within which areas improvement work needs to be done. There should be continuously follow-ups of the PPMs to see if the improvement work has given intended effect and to always keep track of the areas, which need to be improved.

When confident with the PPM, the optimal scenario is to have a PPM for every station where the team leaders are responsible for filling in the matrices within their areas to be able to optimizing every station in the assembly. It is important to keep in mind that the focus of SPA is elimination of deviations and errors and not process development. Hence, using SPA will not reduce nominal cycle times but is a tool to decrease the risk of exceeding the nominal cycle time.

5. Work sampling

This chapter aims to explain the method of work sampling, a method used at VCE to collect data input for MCD. Work sampling will be analyzed to evaluate its reliability. The authors in this thesis participated in the latest round of work sampling and the results will be presented together with an analysis of the method in general, its benefits and disadvantages.

5.1 Work sampling methodology

Work sampling is method used for measuring time utilization and sometimes also used as an indirect measurement of productivity [26]. The method does not only provide information about the amount of time the operators spend on value adding respective non-value adding activities, it can also identify factors affecting the productivity, either positively or negatively [27].

Work samplings are series of instantaneous observations of the operators on the shop floor during their work. At the end of the study the individual observations, assessed either to be value adding or non-value adding, are compiled together to show the distribution between the both. An advantage with work sampling is that it is an inexpensive, easy and quick way to analyze several operators continuously compared to other methods such as time studies, where the focus only is on a few operators. In order to extract as much as possible from work sampling it is essential to conduct it continuously [27].

Since it is desirable to allocate the different non-value adding activities, e.g. transportation, waiting and rework, it is important to define what categories in which to divide work. One of the challenges with work sampling is to attain well-defined and significant categories in a reasonable amount to keep documentation of the observations simple and accurate. Different tools such as papers and handheld computers can be used during sampling, but it is recommended to use computers when analyzing the large amount of data [27].

Before sampling it is essential to decide sample size and accuracy, frequency and length of the data collection as well as the route of how to sample and which tools to use [28]. To avoid anxiety of the observed operators and deviance from normal behavior during the observations, all parties involved must be informed about the method in advance. It should be pointed out that the main purpose is to evaluate the conditions for productivity in order to make improvements, not to evaluate the operators [27].

The choice of assessors is crucial when sampling. To be able to document the work activities correctly, the assessors' knowledge about the work process is of great importance. With good knowledge of the work process it will also be easier for the assessor to analyze productivity problems and to see improvement opportunities [27].

The sampling procedure itself is simple. The assessor has a route he walks and each operator on the route can be seen as a sample. An observation is like a snapshot. The assessor should document which activity the operator is performing at the exact instant moment that the observation takes place [27]. To ensure that all activities have an equal chance of being observed the observation times should be chosen randomly. It is important not to guess the activity performed. If it is unclear which category it belongs to it is better to leave a comment and discuss it afterwards instead. To make sure to get representative data the sampling should be conducted during normal working conditions, i.e. not during peak or off-season [28].

5.2 Confidence interval

When determining the accuracy of the results from work sampling a confidence interval can identify the number of observations required. A high confidence level leads to a higher degree of safety, but also to a wider interval. The higher the number of observations is, the smaller the interval is [29]. A common confidence level, which is often used as a standard, is 95 %. Using a 95 % confidence level means that the real value is covered by the calculated interval with a certainty of 95 %. The calculations for the confidence interval are presented below.

n = number of observations

P (value adding activities) = p

X = number of value adding activities of the *n* observations

$X \epsilon \ Bin\ (n, p),\ \ p^* = \frac{X}{n}$

$$p^*(1-p^*) * n \ > 10 \text{ (a condition for the binomial distribution to apply)} \qquad 5.1$$

$$The\ confidence\ interval: I_p = \left(p^* - \lambda_{\frac{\alpha}{2}}\sqrt{\frac{p^*(1-p^*)}{n}},\ p^* + \lambda_{\frac{\alpha}{2}}\sqrt{\frac{p^*(1-p^*)}{n}}\right) \qquad 5.2$$

95 % $confidence\ interval\ \rightarrow \lambda_{0,25} = 1{,}96\ (table\ value\ of\ standard\ normal\ distributions)$

Through derivation it is clear that p* = ½ will lead to the broadest interval. If the probability of the value adding activities is unknown and the confidence interval has to be no broader than a predetermined number, using p* = ½ will guarantee the width of the interval. If the width of the interval for example needs to be decreased to half, the number of observations needs to be increased four times [30].

5.3 Current situation

VCE uses work sampling as an indicator of how efficient the assembly is. The objective is also to see if there are any improvement opportunities, especially within line balancing or in general. Furthermore, work sampling has also been used as data input for MCD. VCE has some earlier experience within the method, but it was only conducted once on a couple of stations, due to lack of time. Except for being a basis for the MCD, there is a plan for using work sampling in the beginning of every period with a new takt time and in the end of the periods to evaluate how the assembly process has developed in each work area. A work area contains a couple of stations; often there are three stations in one work area. For each work area there is one team leader. Work sampling will also serve as a support for the team leaders to identify areas of improvement possibilities.

The machine models vary widely due to if they are lightly or heavily equipped. The variety of total assembly time ranges between 41 and 66 hours. The method to balance the stations at VCE has been done by leveling, a method to control variability by sequencing jobs to increase capacity utilization. Labor will be more evenly distributed between high and low demanding products and it will protect the labor from volatility when using leveling [31]. Stations and type of machines assembled for sampling has been chosen randomly even though the workload of them varies widely. To reflect reality, the operators chosen for sampling have been ordinary workers to get representative data. Thus, operators new to the stations have been excluded from work sampling.

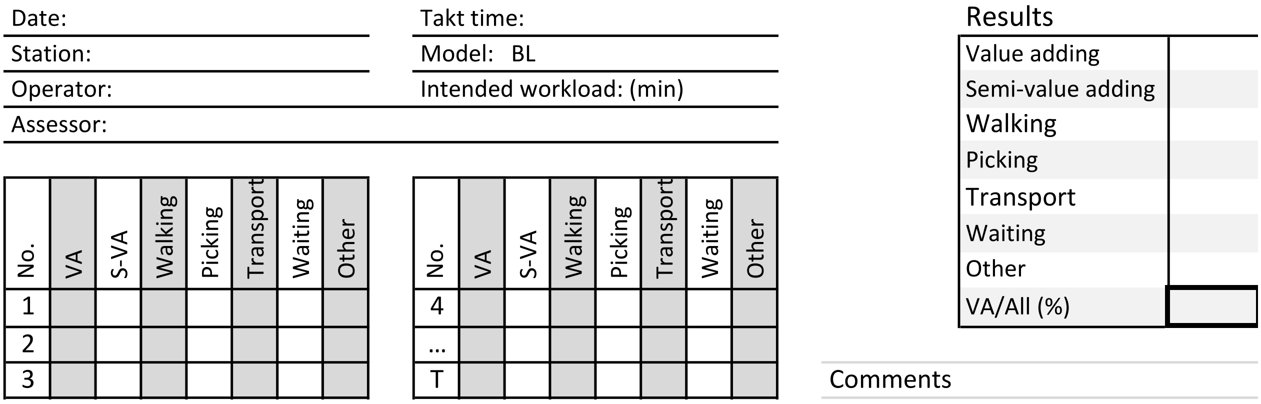
When sampling, a template is filled in with the names of the observed operators and their respective station. The templates also contain categories; one column for value adding (VA), one for semi-value adding (S-VA) and several columns for non-value adding activities. The non-value adding categories on the first samplings at VCE were waiting, transportation, and other. The observations are conducted during a full cycle time since work sampling is supposed to reflect normal circumstances and have to stop if something unpredictable happens, for example when there are line stops.

When VCE first implemented work sampling, groups of two or three persons discussed the different categories and how work sampling should be implemented to avoid different interpretations.

VCE has had no concerns regarding the confidence intervals of their work sampling to know the statistical significance of their results [32].

5.4 Improvements of work sampling at VCE

The template for work samplings developed for this thesis was based on the prior template and can be seen in Figure 5.1. When a new cycle time begins observations were made every minute and filled in by the corresponding number, i.e. the first observation is documented as a dash under the correct category. Changes for how VCE performs work sampling were primarily the adding of categories and clearly defining them, which had not been done before. Also, the time perspective was added to see when certain activities were observed during the takt time. The result of the latter aspect showed that most waiting occurs during the last minutes of the cycle time, indicating that the stations are not well balanced and since waiting normally occurs in the end of the cycle time, the time aspect could be considered to be unnecessary. The time aspect shows at which time the operator finished his work by using the time line, but this could be documented by noting the time when the operator was finished. The results can then be compared to the expected time of work, showing how well intended and actual workload match. A mismatch indicates that an update of the distribution of the workload needs to be done. Categories apart from *Waiting* have no significance of how they are distributed of over the cycle time.



Date:
Station:
Operator:
Assessor:

Takt time:
Model: BL
Intended workload: (min)

No.	VA	S-VA	Walking	Picking	Transport	Waiting	Other
1							
2							
3							

No.	VA	S-VA	Walking	Picking	Transport	Waiting	Other
4							
...							
T							

Results

Value adding	
Semi-value adding	
Walking	
Picking	
Transport	
Waiting	
Other	
VA/All (%)	

Comments

Figure 5.1 exhibits the template used for work sampling. T is the takt time.

The purpose of work sampling is to visualize the time distribution of value adding (VA), semi-value adding (S-VA) and non-value adding activities and to evaluate the work and then make it more efficient by reducing waste and losses. Another achievement with work sampling is to compare results with time to follow the improvements. The non-value adding activities need to be clearly defined to be able to identify them for improvements. The categories used for the first samplings at VCE were not clearly defined and this they have been expanded and defined as follows:

- VA; connecting electronics, hydraulics and mechanics and gluing.
- S-VA; unpacking, applying primer, documenting, and bleeding.
- Walking; walking empty handed.
- Picking; collecting parts/tools within three steps from the working spot.
- Transporting; walking more than three steps with parts/tools.
- Waiting; talking or doing nothing.
- Other; testing, cutting, checking, adjusting, regulating.

The categories *S-VA* and *Other* contains many sub-categories, not to have too many categories while sampling, but there is room for comments on the template to further describe the activity. The drawback of having too few categories is to find solutions for widely defined activities. Having many categories makes it easier to see the real situation and to find a root cause of it to resolve the problem. However, having too many categories makes it difficult to choose the right one due to time pressure and increases the risk for the assessors of having diverse interpretations of the activities.

The non-value adding activities need remedies and below follows suggestions of such:

- S-VA; depends on activity, for instance unpacking, if not necessary, could be reduced by negotiation with supplier to receive goods without plastics covers if not necessary.
- Walking; make spaghetti-maps to visualize the movement of operators.
- Picking; investigate the possibility of using kitting.
- Transporting; having gear closer to work area and kitting.
- Waiting; balance operators workload.
- Other; remedy depends on the type of loss.

Categories were chosen to represent the most common activities without having too many of them. What is important about them is to have a remedy for each category, which is not the case with *S-VA* and *Others*, which can only be further treated through comments made during sampling. Ideas such as having more categories or writing the categories instead of dashing them were rejected to keep documentation simple. Overdesigned methods tend to get less devotion and are hence error-prone and subsequently results will be of poorer quality.

Another change made was that a trial round were implemented. The categories were first discussed mutually among the assessors, as in the first rounds of work sampling, but this time a trial round were conducted followed by another round of discussions to align the interpretation of the assessors.

5.5 Results of work sampling at VCE

The results from the work sampling made after the improvements are presented in the two sections below. In section 5.5.1 the result for the entire assembly line are presented and in section 5.5.2 the results for each work area on the assembly line are presented.

5.5.1 Work sampling on all work areas together

The distribution of the activities on the sampled work areas is presented in Table 5.1. The table also shows the width of the interval, for which it is 95 % confident that the interval covers the real value, for each activity. For example, the real value for the share of value adding activities can be found in the range of 38.9 ±3.2 % with 95 % confidence.

Since an interval of a number of percentages does not say much about how the variances affect the results, calculations of data from work sampling have been made to show the variances in cost and hours per year for all operators in the observed areas, see Table 5.1 It is assumed that one work day, without breaks and meetings, corresponds to 433 minutes (according to VCE) of direct work on the assembly line, the number of working days per month are 20, the number of operators are 54 and the wage is 60 zl/h per operator.

Table 5.1 exhibits the result from work sampling at VCE. Zl is short for zloty, the Polish currency.

				Error margin		**Expected values**	
Activities	**No. obsv.**	**Share [%]**	**Interval [+/- %]**	**Time [h/yr]**	**Cost [zl/yr]**	**Time [h/yr]**	**Cost [zl/yr]**
Value adding	345	38.9	3.2	2 998	179 903	36 337	2 180 214
S-VA	170	19.1	2.6	2 420	145 217	17 905	1 074 308
Walking	52	5.9	1.5	1 444	86 663	5 477	328 612
Picking	105	11.8	2.1	1 986	119 180	11 059	663 543
Transport	83	9.3	1.9	1 791	107 440	8 742	524 515
Waiting	70	7.9	1.8	1 658	99 462	7 373	442 362
Other	63	7.1	1.7	1 579	94 760	6 635	398 126
Total	888	100				93 528	5 611 680

Seeing how the variances impact cost and time makes it easier to determine how much error to allow, since it is easier for a manager to say that ±5 000 hours is an acceptable error instead of ±5 %, not knowing the number translated into time and cost.

5.5.2 Work sampling on individual work areas

In Table 5.2 the distribution of the activities in each work area is shown and its corresponding confidence interval. As it shows, the intervals are broader than in the result for the entire assembly line. Hence, the accuracy is poorer for only one work area at a time than for all of them together. The work area with the poorest accuracy has an interval of ±9.9 %, while for all work areas together it is ±3.2 %, a much lower number. The reason for this is a higher number of observations on the assembly line than on each work area. This implies that the results for each work area are less reliable than the result for all work areas together.

Table 5.2 exhibits the results of the share of each activity for each work area and their confidence intervals. All values are expressed in % and the intervals are ± %.

	WA1		WA2		WA3		WA4		WA5		WA6	
Activities	**Share**	**Interval**	**Share**	**Interval**	**Share**	**Interval**	**Share**	**Interval**	**Share**	**Interval**	**Share**	**Interval**
Value adding	27,5	6,1	48,0	9,9	44,4	7,9	40,3	7,7	40,1	7,9	40,2	8,4
S-VA	21,6	5,6	21,4	8,1	11,8	5,1	24,0	6,7	11,6	5,2	25,0	7,4
Walking	8,3	3,8	1,0	2,0	4,6	3,3	3,2	2,8	9,5	4,7	6,1	4,1
Picking	11,3	4,3	12,2	6,5	15,0	5,7	11,0	4,9	10,2	4,9	11,4	5,4
Transport	14,7	4,9	8,2	5,4	7,8	4,3	9,7	4,7	3,4	2,9	9,8	5,1
Waiting	9,8	4,1	0,0	0,0	15,7	5,8	3,9	3,1	9,5	4,7	4,5	3,6
Other	6,9	3,5	9,2	5,7	0,7	1,3	7,8	4,2	15,6	5,9	3,0	2,9
No. obsv	204		98		153		154		147		132	

5.5 Analysis of work sampling

When work sampling was first conducted at VCE the groups did not get to discuss mutually afterwards what was concluded in the individual group meetings and there was no trial round before the real work sampling was conducted. After the first round it became obvious to the observers that they still had different interpretations of the categories, even though there had been discussions before the round the interpretations of the activities were different and some more discussions were needed to align the observers.

During work samplings it was evident that the interpretations were made more similarly and the observations reflected reality better when having someone, in this case a team leader, in the group who knew the processes. This person should be able to tell for instance when extra ordinary tasks or overproduction is performed. It is also important not to interrupt the observed person by asking the operator about the operation performed at the moment, if it is hard to determine what kind of activity that is performed. This is because the operator will probably answer what the purpose of the operation and not what was actually performed in the exact moment of the observation. Interruptions can also make the observed person deviate from their normal pattern. Hence, the observations will not reflect reality.

To gain objective results of the observations the assessor should be in movement, i.e. walking between the observed people. If the observer is idle there is a risk of getting affected by the observed operators earlier activities and log those instead of the observed act at the intended moment. For example, if the observer stays on the same spot during the observations and sees that the operator performs various value adding activities there might be a risk that the assessor chooses the observation moment when the operator is performing a value adding activity, instead of taking a random observation moment. Using a time advice that generates random times is a solution to keep track of when to log observations and gain as much randomness as possible.

Other parameters affecting accuracy and reliability of work sampling are the variety of machines, the number of stations observed and the skills of the operators. It is essential for the result to make a selection of operators, stations and machines for work sampling that is representative for the assembly line. Only observing operators with low skills operating on heavy machines at only a few of the existing stations will give a misleading result. Operators with low skills will most likely not have the same distribution between activities as a normally skilled operator. For example, a low skilled operator would need more time to assemble than a normally skilled operator, which would lead to a higher frequency of value adding activities and lower frequency of waiting. The same reason accounts for only observing highly experienced people; there is a chance that they finish their operations earlier than expected, implying a higher frequency of waiting and maybe also of overproduction. To gain more accurate results the group of observed people should be normally skilled or consist of a mixture of skills. Also, being observed might make them feel stressed and due to that they might work faster or deviate from the normal in other ways. To minimize this risk it is important to inform the operators of the purpose of the work sampling.

As for the machines, the operations for assembling a machine varies between 41 and 66 hours, due to the 150 options available for a single machine. Depending on what type of machine that is being assembled during observations the results will be different. A heavy machine will imply higher frequency of value adding activities and a lower frequency of waiting and over production than for a light machine. A solution to make better estimations of which machines to observe could be to identify the distribution of the machines assembled to see which type, or what assembly time, is more common or to choose a selection of machines representative for the average production.

Since all stations are different the allocation of activities will also differ. Therefore, it is not suitable to only do observations on a few stations when evaluating the entire assembly. As many stations as possible, ideally all of them, should be included in the observations.

Using confidence intervals is a good way to ensure the accuracy of the sample but the calculations does not take the human factor into consideration. Even if an error margin of ±3,2 % (the result of value adding activities in this case) is a good accuracy for this purpose, it only applies if the observers have interpreted the different activities similarly and have not made any guesses when being uncertain. Aligned assessors are essential for good sampling results and that is why it is important to put effort in ensuring that interpretations among the assessors are the same. Without alignment, the accuracy of the results cannot be ensured and the observations can only be used as pure observations without any statistics for the different activities.

Since the same assessors did the majority of the observations and most of the stations were included during this round, these sources of errors could be seen as relatively small. However, the types of machines were not taken into consideration, which implies that the accuracy of the result cannot be determined.

5.6 Discussion

If the alignment of the assessors is ensured, the selection of operators, machines and stations chosen is representative for the assembly line, the accuracy is ensured by a confidence interval and the observations are made randomly, work sampling can be seen as a good data gathering method and a reliable source for the MCD. If one or more of these factors are not fulfilled the sources of errors will increase and it becomes hard to determine the actual accuracy of sampling and the results of the MCD will be of poorer quality.

Another method, accept for work sampling, that can be used in the same purpose for MCD is a time study where the time for each activity is documented instead of looking at the frequency.

Since a time study is more time-consuming (only one person at a time can be observed) than work sampling and has the same sources of errors, the risk of different interpretations and the selection of operators, machines and stations to observe, the work sampling is a more suitable and effective method for VCE.

Using work sampling as an evaluation method to see the development of assembly processes from the beginning of a period with a new takt time to the end of the period for every work area requires a higher number of observations than during the recent implementation, see Table 5.2. The same principles for work sampling apply for each individual work area as for the entire assembly line. With too few observations or for instance only heavy machines observed at the beginning of the period and only light machines at the end of the period, the results from the beginning and the end of the period will not be comparable and no reliable conclusions can be drawn about the process development.

The real benefit of work sampling can be gained if getting statistics and being able to reflect on the overall evaluation of operators work. Noticing improvement opportunities without going through statistics implies, if possible, that a solution can be implemented faster. However, statistics is important to show where the biggest losses are and some losses might not be identified by pure observations. Nevertheless, making pure observations would be tiring and there is a risk of loosing focus due to monotonous work.

As mentioned above work sampling can function as more than just a tool to measures time utilization; it can also help the persons conducting work sampling, e.g. engineers, team leaders and operators, to open up their eyes to really see what is going on at the shop floor. Besides, implementing the philosophy of value adding and non-value adding among personnel gives new perspectives when analyzing the assembly and can open up for further improvements. Reflecting on the various activities conducted by the operators and writing comments in the comment field can be as effective, if not more, to discover areas of problem and of improvement possibilities as getting the result of the distribution of activities.

Work sampling is a method that can be used in various industries and it is an efficient method for measuring the time utilization as long as the sources of error are taken into consideration. The higher degree of standardization, the easier it is to get accurate results.

5.7 Recommendations

The recommendation for VCE is to continue with work sampling as a source of data for MCD, but the selection of stations, machines and operators must be done more carefully than it is done today to achieve a reliable result. Before they start to sample it is essential that they do a trial run to ensure the alignment of the assessors' interpretations. The minimum number of observations needed should be calculated by using confidence interval.

Using work sampling to see how the development of a work area has proceeded from the beginning of a period with new cycle time to the end of that period will require a higher number of observations than during the previous loops of work sampling. Also here should a confidence interval be used for the calculations of the number of observations needed for each work area if the statistics should be compared.

6 Conclusions

In his chapter the answers to the research questions are presented based on the literature review, observations and analysis at Volvo Construction Equipment. In the end of this chapter there is a section where future research areas are presented.

This thesis has been accomplished in order to evaluate how VCE can improve their work with MCD. Furthermore, the cost model SPA and a method by Son have been evaluated in search for an alternative cost model for VCE. The data collection tool, work sampling, is used as an input collector for MCD. What has not been evaluated at VCE is the reliability of work sampling and the second purpose of this thesis has been to investigate the reliability of this method.

6.1 Answers to the research questions

How can Volvo Construction Equipment improve their work with manufacturing cost deployment?
Dedication is essential for how successful an implementation of a method on a company will be. The lack of it at VCE has led to absence of significant results. Unless this changes, the results from MCD will no be improved. Therefore, it is of great importance and it should be a first step of improvement to convince the management team about the benefits of the method and make sure that they are completely committed to it. To set goals and to clarify which expectations there are of achieving results from MCD is a way of getting the involved personnel motivated to complete the D, E and F matrices and achieve desirable results.

The B and C matrices are deficient compared to the original matrices and need to be redesigned in order to better match the original matrices. The broad process steps in the matrices make it hard to locate the causes of the losses and should instead be divided into work areas to easier locate the losses. The reason for choosing work areas instead of stations is that a substantial amount of work is required to collect reliable data for the stations.

When implementing a new method it requires that the involved personnel put enough effort into it before it can run smoothly. This is something VCE still has to do even though two loops of MCD have already been finished. MCD should be a regular part of VCEs improvement work with continuous follow-ups. To achieve continuity there are some prerequisites: there need to be systematic ways of how to collect the data needed. The team leaders are preferably to be responsible for most parts of the data collection since they are highly knowledgeable in the operations and can be a great resource in the improvement work.

Today VCE has divided the resultant losses in the matrices into large process steps. To make it easier to locate where the losses occur the process steps should be smaller, for instance they can be divided into work areas to be able to locate where waste and losses occur more precisely.

Standards of how to calculate costs should be set to ensure the validity of the results. This will enable the comparison and evaluation of results from earlier loops of MCD.

The A matrix is currently, and originally, using a scale of 1, 2 and 3 to prioritize losses. To get a better view of which areas to prioritize and to easier distinguish the losses of high and low prioritization, a recommendation is to rate losses with 1, 3 and 5 instead, which means that losses of the highest priority will also be highlighted the most. Having too many losses with the highest priority makes it harder to focus and there will have to be a priority within the prioritized losses. A goal is to have maximum ten percent losses with the highest priority.

Is there another manufacturing cost model, apart from MCD, that would be suitable for VCE and if there is, how does it differ from MCD?
MCD is a cost model with the purpose to eliminate waste and losses. Another important factor when looking at cost is to eliminate deviations and make existing processes flow without errors. Therefore, SPA would be an alternative cost model since it reduces cost by focusing on eliminating deviations.

The major differences between MCD and SPA are summarized in Table 6.1. They differ primarily in their focuses where MCD has a strong focus on reducing waste and losses using a holistic view while SPA focus on eliminating deviations mainly in the operations. The difference between the MCDs waste and losses and SPAs deviations is merely the names. What they both strive for and have in common is the identifying of cause-resultant relationships. The approaches are easy to follow, though MCD has a more structured approach since all steps are included in the matrices. SPA considers the utilization, which MCD does not, and emphasizes the importance of using released capacity. Finally, cumulated material cost, total manufacturing cost and cycle time is considered only in SPA.

Table 6.1 exhibits the major differences between MCD and SPA.

	MCD	SPA
Focus	Eliminate waste and losses in manufacturing processes	Eliminate deviations in manufacturing processes
Cause-resultant relationship	Visualized in matrix B	Visualized in the PPM
Waste and losses	Identified in matrix A	Identified in the PPM
Total profitability	Not included	Not included
Approach	Clear and easy to follow due to the matrices	Has an eight step methodology
Utilization	Not included	Calculates it and emphasizes the importance of using released capacity instead of just decreasing utilization
Cumulated material cost	Not included	Material costs cumulate as parts are processed, calculated with the cost relation
Total manufacturing cost	Not included	Is considered using the cost relation
Cycle time	Not included	Is considered in the cost relation when calculating manufacturing cost

SPA is a structured, well-defined and user-friendly method to set the foundation for changes and development for a production system by identifying loss terms such as quality and downtime. Additionally, the factors are well defined and include cycle time, cumulated material and especially utilization, which are important factors that are not considered in MCD.

Can work sampling be seen as a reliable source of data when evaluating production processes?
Work sampling in itself is a simple concept to attain the distribution between value adding and various non-value adding activities, but the potential error sources make the method complex. As discussed in chapter 5, the error sources mentioned need to be taken into consideration and eliminated for work sampling to be considered as reliable. For companies similar to VCE, where the majority of the workload is performed manually and where there is a significant variance among products, the sources of errors in work sampling are more and larger than for companies with standardized products, processes and less manual work. On the other hand, this counts for most data collecting methods: the more manual work and the more complex the manufacturing system is, the harder it is and the more effort is required to achieve accurate data.

Conducting work sampling with great care, awareness and well-made preparations will lead to reliable results, though they will never be completely accurate. Using confidence intervals will indicate on what level the accuracy is, provided that the error sources are eliminated or reduced to the maximum.

If the company is prepared to put the efforts needed to eliminate the sources of errors and to conduct the number of observations needed to acquire the desirable accuracy of work sampling it can be seen as a reliable source of data when evaluating production processes. Even though the result will not reflect reality to one hundred percent, it will be accurate enough to, for instance, evaluate the efficiency of a production line or be used as input for a manufacturing cost model.

6.2 Future research

The focus of this thesis has been the assembly at VCE and therefore the PPM was developed for the stations in the assembly. Even though the SPA, which includes the PPM, was developed for manufacturing production systems it would be interesting to investigate if and how it could be applied on logistics at VCE. Windmark & Andersson has been investigating the issue of applying logistics on SPA and has developed a cost model to determine the cost for inbound logistics, which they connect to Ståhl's manufacturing cost model [33]. This approach would be interesting to investigate since adding logistics would give a more holistic view of the production cost.

8 Discussion

This chapter aims to evaluate the work of this thesis, presenting reasons for why and how the research questions were chosen as well as general thoughts and difficulties throughout the work.

When searching for a thesis project in the area of industrial production the authors got in touch with VCE. The main aim was to find a project in which the company had great interest to get the full devotion from them, since it would be great motivation for the authors to support them in the issue. The project area of this thesis was initially to be MCD. When arriving to VCE it was clear that they had little experience within the method and had made little success with implementing it. The purpose of the thesis was initially to improve the execution and thus the results of MCD, but as the problem with MCD appeared to be the data collection it came to be an additional focus of the thesis. A major aspect, which the authors were fully aware of, was the relation between MCD and its data and only focusing on data collection without considering the integration with MCD changed the direction of the thesis. The result became a deeper investigation in the measurement tool work sampling, partly as a tool by itself but also as a part of MCD.

Considering the focus of data collection the thesis did not get the depth within MCD as the authors had wished from initially, although the main topics, MCD and work sampling, are clearly connected since work sampling is a tool used within MCD. Another tool for MCD called time study was considered but was rejected due to the heavy workload and time consumption.

The current situation and conclusions regarding recommendations of how to improve their MCD is sometimes not profoundly motivated and underpinned with references to the literature. The results from the cost model area derives from interviews and observations and has had no platform for how to interpret the information in addition to the theory of the cost methods. Hence, there has been little results to base analysis and results on. Also, this fact has made it hard to separate results, interpretations, analysis and conclusions, since conclusions are to be drawn from results and analysis.

When evaluating the part about work sampling, the authors conclude that the results and conclusions for the third research question concerning work sampling are mainly based on literature reviews and the execution of work sampling at VCE. The samplings were made randomly and the goal was to sample on all work areas. The type of machine was not taken into consideration for the samplings. If the study was to be made again it would have been interesting to investigate how much the results would differ by comparing observations including only heavily equipped machines with observations including only lightly equipped machines, or only observing experienced operators compared to beginners.

The theory used to compare the manufacturing cost models was the theory presented about the cost models. An idea could have been to use a platform for evaluating the models.

The language barrier at VCE has not had great impact on the work but has indeed been an influencing factor. The greatest advantage would have been to be attending meetings at planning level; instead the authors were informed of the outcomes of the meetings. Also, it would have been possible to discuss work sampling and general problems for application of PPM with the team leaders.

9 References

[1] Doganaksoy N. & Hahn G. J., "Getting the Right Data Up Front: A key Challenge", *Quality Engineering*, no. 24, pp. 446-459, 2012.

[2] Jönsson, M., "Cost-conscious manufacturing – Models and methods for analyzing present and future performance from a cost perspective", *Division of Production and Materials Engineering, Lund University*, 2012.

[3] "Looking back - moving forward, Volvo Construction Equipments första 175 år", *Volvo CE,* 2007. [Online]. Available: http://www.volvoce.com/SiteCollectionDocuments/VCE/History/Company/175%20years%2012A1003961-0711.pdf. [Accessed 2014-04-29].

[4] "A group of high-power companies", *Volvo CE,* 2014. [Online]. Available: http://www.volvoce.com/constructionequipment/corporate/en-gb/AboutUs/about_volvo_group/Pages/about_volvo_group.aspx. [Accessed 2014-04-29].

[5] "A Global Group", *Volvo Group,* 2014. [Online]. Available: http://www.volvogroup.com/group/global/en-gb/volvo%20group/Pages/aboutus.aspx. [Accessed 2014-04-29].

[6] "Company culture – The Volvo Way", *Volvo Group*. [Online]. Available: http://www.volvogroup.com/group/global/en-gb/career/life%20at%20volvo%20group/ourculture/Pages/ourculture.aspx. [Accessed 29-April-2014].

[7] "Volvo Group core values", *Volvo Group,* 2014. [Online]. Available: http://www.volvogroup.com/group/global/en-gb/volvo%20group/ourvalues/Pages/volvovalues.aspx. [Accessed 2014-04-29].

[8] Pawlik, G. Production Engineer. Volvo Construction Equipment, Wroclaw. [Interview] 2014-04-07.

[9] "Volvo Construction Equipment", *Al-Futtaim Auto & Machinery Company LLC.* [Online]. Available: http://www.famcouae.com/13/Volvo-Construction-Equipment.aspx. [Accessed 2014-07-22].

[10] "Manufacturing quality the Volvo Way", *Volvo CE*. [Online]. Available: http://www.volvoce.com/constructionequipment/corporate/en-gb/quality/product_life_cycle_quality/manufacturing_quality/pages/manufacturing_quality.aspx. [Accessed 2014-04-29].

[11] "The Volvo Way mot ökad konkurrenskraft", *Lindström, K.* [Online]. Available: http://www.leanforum.se/dokumentation/Lindstrom.pdf. [Accessed 2014-04-29].

[12] "The Volvo Production Systems's Model". [Online]. Available: http://media.aerotrainees.se/2011/12/ma0901C.gif. [Accessed 2014-05-06].

[13] Arbnor, I. & Bjerke, B., “Methodology for Creating Business Knowledge”, 3rd edition, SAGE Publications, California, 2009.

[14] Höst, M., Regnell, B & Runesson, P., “Att genomföra ett examensarbete”, 1:6 edition, Studentlitteratur AB, Lund, 2006.

[15] Yin, R. K., “Case study research, Design and methods”, 4th edition, SAGE Publications, California, 1994.

[16] Yamashina, H., Kubo T., “Manufacturing cost deployment'', *International Journal of Production Research,* vol. 40, no. 16, pp. 4077-4091, 2002.

[17] Yamashina, H., “Cost Deployment-establishing a SMART cost reduction programme”, *Volvo Construction Equipment*. [Online] Available: https://teamplace.volvo.com/sites/bhl/VPS/CI/default.aspx?RootFolder=%2Fsites%2Fbhl%2FVPS%2FCI%2FShared%20Documents%2FPrioritisation%2FCost%20Deployment%2FTraining&FolderCTID=0x012000864406804B95224B9B08D171B7C6E4ED&View={82FC11BB-22BC-4CD4-A011-979812692021}&InitialTabId=Ribbon%2ERead&VisibilityContext=WSSTabPersistence

Volvo Construction Equipment. Internal. [Accessed 2014-04-10].

[18] Gorazd, P., Business Controller. Volvo Construction Equipment, Wroclaw. [Interview] 2014-04-15.

[19] Lundgren, R., Business Controller. Volvo Powertrain, Skövde. [Interview] 2014-07-10.

[20] Ståhl, J. E., “Industriella tillverkningssystem del II – Länken mellan teknik och ekonomi”, 2nd edition, Division of Production and Materials Engineering, Lund University, Lund, 2012.

[21] Son, Y. K., “A cost estimation model for advanced manufacturing systems”, *International Journal of Production Research*, vol. 29, no. 3, pp. 441-452, 1991.

[22] Özbayrak, M., Akün, M. & Türker, A.K., “Activity-based cost estimation in a push/pull advanced manufacturing system”, *International Journal of Production Economics*, vol. 87, pp. 49-65, 2004.

[23] Chiadamrong, N., “The development of an economic quality cost model”, *TQM & Business Excellence,* vol. 14, no. 9, pp. 999-1014, 2003.

[24] Son, Y. K., “A cost estimation model for advanced manufacturing systems”, *International Journal of Production Research*, vol. 29, no. 3, pp. 442, 1991.

[25] Ståhl, J. E., “Industriella tillverkningssystem del II – Länken mellan teknik och ekonomi”, 2nd edition, pp. 161, Division of Production and Materials Engineering, Lund University, Lund, 2012.

[26] Liou, F-S. & Borcherding, J. D., “Work Sampling Can Predict Unit Rate Productivity”, *Journal of ConstructionEngineering and Management,* March, pp. 90-103, 1986.

[27] Jenkins, J. L. & Orth, D. L., “Productivity Improvement through Work Sampling”, *AACE International Transactions,* csc. 05, pp. 1-7, 2003.

[28] Konorti, E., “Give ratio-delay a chance”, *Industrial Engineer,* November, pp. 34-39, 2012.

[29] “Föreläsning 5, Statistiska metoder”, Linköpings universitet. [Online]. Available: http://www.ida.liu.se/~732G60/Forelasning%205.pdf. [Accessed: 2014-07-22].

[30] Zetterqvist, L., Associate Professor. Lund University, Lund. [Interview] 2014-05-20.

[31] Hüttmeir, A., de Treville, S., van Ackere, A., Monnier, L. & Prenninger, J., ”Trading off between heijunka and just-in-sequence”, *International Journal of Production Economics,* vol 118, pp. 501-507, 2009.

[32] Maleszka, T., Production Manager. Volvo Construction Equipment, Wroclaw. [Interview] 2014-05-05.

[33] Windmark, C. & Andersson, C., “Cost models of inbound logistics activities: supporting production system design”,