CHALMERS
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Production lead time investigation through Value Stream Mapping and Discrete Event Simulation

Master’s Thesis in the Master’s Program in Production Engineering

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Department of Product and Production Development
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Gothenburg, Sweden 2015
Master’s Thesis 2015

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ABSTRACT

Currently more and more customers in the power industry are demanding shorter delivery times. The power industry is highly conservative and producing to stock or standardizing products is not an option. Therefore reducing the production lead time is highly important. This thesis is trying to answer which of the tools, Discrete Event Simulation or Value Stream Mapping that is the most efficient when it comes to estimating and reducing production lead times. There is also a gap in the literature regarding the use of a combination of these tools. In order to be able to compare them a case study was performed at the power products manufacturer ABB, in Ludvika. The case study was divided in the following way: The first step was the building and experimentation of the Discrete Event Simulation and secondly, the Value Stream Mapping project was performed. The areas in focus were: time consumption, competence needed, data availability and accuracy of the results. The results showed that the Discrete Event Simulation is the more accurate tool and it is beneficial in production systems with many product families. Among the negative traits are the need for highly skilled personnel, data availability and plenty of time. Value Stream Mapping is a quick tool for calculating the production lead time and identify possible improvements areas. It is less accurate but easily collected data and the simpleness of the tool makes it an alternative tool. Regarding the use of a combination of them it was concluded that a Discrete Event Simulation could aid the Value Stream Mapping process in the following ways: Make the implementation phase faster by pointing out which improvements to implement and to present a dynamical version of the production system. However, when deciding which of the tools to use it will always be a choice between accuracy and time. The longer time put into finding the production lead time the more accurate it gets.

Keywords: *Discrete Event Simulation, Value Stream Mapping, Production lead time, Lean Production*

Preface

This Master Thesis is written as part of the Master of Science program in Production Engineering at Chalmers University of Technology The project was carried out in cooperation with ABB, Components division, Ludvika - Sweden. In order to protect the interests of the case study company fabricated numbers were used in the results.

Therefore, we would like to thank Henrik Nordén, the Production Engineering Manager of the Bushings department of ABB Components and the Production Engineer Andreas Backström for the opportunity that they gave us and for their continuous support during the whole project. Also, we would to thank the whole team of the GOB production line who took their time to guide us as well as answering questions.

In addition, we would also like to thank Jon Larborn and Anders Skoogh for their supportive supervision and constructive feedback regarding the methods used as well as how to present the results in an academically correct way.

We would also like to thank Pamelina Olsson and Linn Hedström Kuosmonen for their useful input during the opposition of this thesis.

Finally, we would to express our gratitude to our families for their support during our academically life.

Göteborg September 2015

Ioannis Basoukos and Jens Spångberg

List of abbreviations

DES - Discrete Event Simulation

VSM - Value Stream Mapping

TPS - Toyota Production System

SMED - Single Minute Exchange of Die

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1 Introduction

The introduction chapter contains the background of the thesis project. The purpose and aim is also described as well as the delimitations. In the end, a short description of the case study company is included.

1.1 Background

The manufacturing industry of today is facing an increasing competition through the ongoing globalisation. Traditionally the companies in USA and Europe have been able to compete purely on the quality of their products. This, however, has begun to change. Manufacturers in development countries have started to make products of better quality at a lower price. This forces companies to take actions to stay competitive (Friedman, 2007). In order to stay competitive the companies need to increase their productivity by focusing on the traditional problems that they face. One of these problems, is the high pressure from customers of having shorter and shorter delivery times. Meeting a current demand of products could either be done by producing to stock and bound important capital or shorten the production lead time. The latter alternative was investigated in this thesis. The production lead time is defined as the time between a product enters the production and the time it leaves it. (Rother and Shook, 2003). Through the years a number of tools and methods have been developed in order to investigate production lead times. Since Rother and Shook (2003) released the book “Learning to see”, where the concept of Value Stream Mapping (VSM) was explained, the tool has become increasingly popular. Another tool is the Discrete Event Simulation (DES) which according to a survey in Sweden is used by 15% of the questioned companies (Ingemansson. et al, 2002). According to a number of sources the DES is considered more accurate than the VSM (Mahfouz et al, 2011; Xia and Sun, 2013; Rother and Shook, 2003; Singh et al., 2011). Therefore it would be interesting to investigate in what situations DES is preferred for production lead time reduction rather than the VSM and also if DES could complement the VSM.

1.2 Purpose and Aims

Discrete Event Simulation and Value Stream Mapping are two tools that have been used by the industry in order to create efficient production systems and smoother flows. In the literature, there are a number of studies in which DES and VSM have been used to transform future or existing production systems into becoming more Lean (Donatelli and Harris, 2001; Standridge and Marvel, 2006). However, there is a gap when it comes to using a combination of the two tools for production lead time reduction.

The purpose of this study is to provide a well structured and comprehensive understanding about the optional selection between DES and VSM for the stakeholders involved in the production development processes.

The aim of this master thesis project, is to investigate in which situations DES is the preferred tool over VSM, regarding production lead time reduction. Another aim of this project is to examine if DES possibly can complement the VSM tool in this area. In order to achieve those aims, a case study was conducted at ABB. The case study was used in order to answer the following questions:

- When is DES preferred compared to VSM for production lead time reduction?
- How could DES complement VSM in production lead time reduction?

A number of different comparison criterias were used to evaluate the two tools, DES and VSM. The Methodology chapter (chapter 3) contains a description of the criterias.

1.3 Delimitations

The main focus of this project is to investigate if VSM and DES can be used to reduce production lead times. The project will not focus on how the different tools affect the quality and the productivity of the production line. All the different factors that affect the production lead time will not be investigated, the study is mainly to examine which tool is preferred over the other and if there are complementary effects. The same is true for the ergonomy of the workplace, no investigation will take place of how tasks are being performed or the quality of the working environment. Lastly, the usage of the tools in similar or dissimilar production environments will not be considered.

1.4 Case study company presentation

ABB is a world leading company within the power products and automation business. The headquarters is situated in Zürich, Switzerland and in total the company has 140,000 employees spread out over 100 different countries. The name is an abbreviation of ASEA, Brown and Boveri, the companies merged in 1988 to form ABB. In Sweden there are 9,000 employees, 2,700 of them work in Ludvika where this thesis project takes place.

The Components department of ABB, manufactures a variety of surge arresters, tap-changers and bushings depending on the customer demand. This report is focused on the analysis of a production facility for transformer bushings. An oil impregnated transformer bushing can be seen in Figure 1 below.

Figure 1 GOB oil impregnated transformer bushing.

The production flow of a transformer bushings is divided into five different processes: winding, assembly, vacuum - oil, testing and packaging process. The Figure 2 shows the production system, as a flow chart. A more detailed description of the examined production flow is presented in the chapter 3.1.

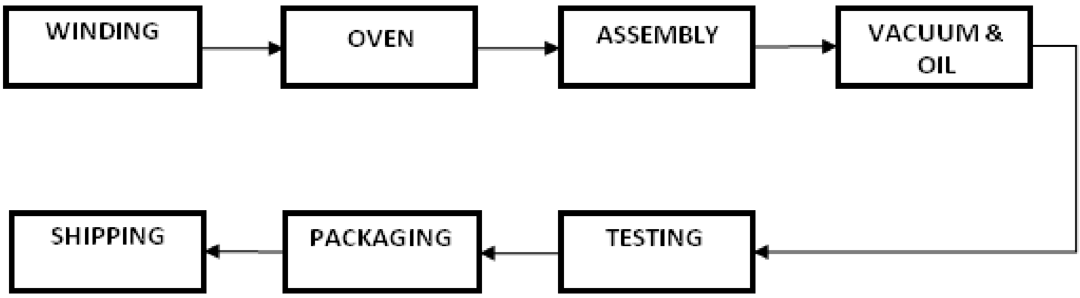

Figure 2 ABB's bushing production processes.

2 Frame of reference

The frame of reference chapter explains the different tools used. The first sub-chapter presents introductory facts about production development, followed by an introduction to Discrete Event Simulation. Further, the concept of Lean Production is explained through the Toyota Production System sub-chapter. Finally the representation of production lead time in DES and VSM is described.

2.1 Production development

The production development area relates to methods and tools used for improving production processes. During the history many different tools and methods have been used. Henry Ford used time studies to make work tasks as optimal as possible. The introduction of quality circles in the 60s showed the importance of quality (Womack et al, 2007). Today, the production development is greatly affected by the Lean philosophy as well as technical areas growing such as computer simulations and 3D scanning. The future production processes will focus on being as sustainable as possible in the three sustainability areas: social, environmental and economic. That transformation will affect almost all parts of the production system, from product development to work force and after sales market. Based on that fact, new tools and techniques should be developed in order to upgrade the existing production systems and make them more sustainable in the long run (Grabot et al, 2014).

The case study company, ABB desires shorter delivery times. There are different ways to fulfill that. One way is to produce to stock. This, however, is something that is not possible within the power products industry. Most of the customers are very conservative and do not want to standardise the products. The bushings produced have a life expectancy up to 30 years. The alternative possible for ABB is to lower the production lead time and thereby make the bushings flow faster through the production system which results in a faster delivery to the customers.

2.2 Discrete Event Simulation

In this sub-chapter, the usage and the basic stages of developing a DES are explained. That gives the reader a broad overview regarding the importance and applications of DES, in a wide area of production systems.

2.2.1 Background of DES

The simulation model of a real production system can be described as a computerized representation of itself. Through analyzing various scenarios, a better understanding of the model's dynamical behaviour can be achieved (Shannon, 1975; Banks, 2005).

2.2.2 Different types of simulation models

The following subchapter explains different types of models that can be used in simulations. Different types of models are often combined, for instance a dynamical model which uses stochastic data and states is called a discrete event model. That is the type of model used in this thesis. The model is explained more in detail below.

2.2.2.1 Static and Dynamical models

A dynamical system change is dependent of the time factor, without time the model cannot be dynamical. Each model that changes in time can be considered dynamical. A static model represent a snapshot in time and remains constant. A static model can simulate different outcomes for a certain time.

2.2.2.2 Deterministic and Stochastic models

In a deterministic model the outcome of the model is predetermined. Each action taken in the model can be clearly traced through a chain of actions (each predetermined). A stochastic model is the complete opposite, the outcome of the model is based on a number of occurrences, each dependent of a stochastic value which decides what each action will do. It is in other words impossible to predict the outcome, however one can make assumptions in what range the output will be and through repeating the chain of occurrences a number of times a more secure result can be established.

In this thesis project an event oriented model is used. It will also be a stochastic model. The common term for this sort of model is the discrete event model. The model is built on states, for each new event a stochastic calculation is done in order to decide the new state (Van Inwagen, 1986).

2.2.3 DES in detail

Production simulation through DES is based on the idea that you create a simulation which uses triggers that show up through a statistical distribution. When each of these triggers happen you create a discrete event that affects the simulation. In a simulation time is an important part. Compared to other methods the simulation is dynamic and the result differs over time.

2.2.3.1 Advantages and disadvantages of using DES

Before using DES in an organization there are a number of different advantages and disadvantages to be considered. Among the advantages the possibility to experiment without disturbing the production is a very important one. It also relates to the possibility of simulating a production start-up when introducing a new model. Through that way more time can be spent on simulating in a computer rather than having a slow warm up time in the production. DES results are often easily presented and quick analysis of small changes can be made easily even though the user has limited experience with simulation work (Banks, 2005). Another advantage is the fact that a DES model helps in creating consensus of which improvements to implement (Mahfouz et al, 2011). The main disadvantages of DES are that it is time consuming, and if the organization is not mature enough they might have difficulties in interpreting or using the results. For the inexperienced user, a DES result might look precise but it is important to remember that the result is fully dependent on the quality of input data that the model has. Inaccurate data leads to faulty results. The same goes for the fact that simulating human behaviour is very difficult. These disadvantages have led to the fact that DES is not yet fully accepted among companies (Banks, 2005; Skoogh, 2013).

Table 1 Advantages and disadvantages of using DES

Advantages	Disadvantages
Possible to experiment without disturbing the production.	DES can be time consuming, need experienced people to perform the model building.
Faster development processes - less warm up time of a new model.	DES often experiences difficulties being accepted within organizations.
Both visual and pedagogical.	Even though the model is wrong, a DES gives the impression of being precise.
Can be used both to identify and find solutions to problems.	A DES is a powerful tool to simulate machines, but simulating peoples are much more difficult.
A complete model can be used for quick analysis.	
Compared to static methods it considers the dynamical traits of the system.	

2.2.3.2 AutoMod 12.4

The AutoMod 12.4 software was developed by the company Applied Materials Inc.. The software is suitable to be used in many different kind of businesses, all from manufacturing to military, medical, logistics and transportation simulations (Banks, 2005). AutoMod was chosen for this project since the authors had previous knowledge of the software. The version used is a student version which has limitations regarding the number of entities allowed.

2.2.4 Method of DES

The DES was performed according to the steps provided by Banks (2005). Starting with conceptual model, data collection, building of model, verification, validation and in the end a creation of an operational model which focused on the reduction of production lead times. The building of the model were done in steps where verification and validation of each step was done before proceeding to the next step. Each step represents a function in the production line.

2.2.4.1 Conceptual Model

A conceptual model is a simplified drawing of the real system, it is created in order to get a better understanding of the process and the data flow (Banks, 2005; Robinson, 2004). A well- constructed conceptual model is necessary before the development of the computerized DES model. During the development process of the conceptual model, the main stakeholders of a project, (such as the modellers and the management of a company) should continuously have a constructive and open dialogue regarding the information that should be included in the model and the level of detail of it.

In this report, the authors who were the modelers, started the development of the conceptual model as soon as they had finished the work practice. The main stakeholders of this project, from the company's side, were the production engineering manager and the production engineer. Both of the stakeholders had a supervisory role of the examined production line. Based on the literature review and a number of meetings, the conceptual model was continuously updated in order to conclude the main areas that were of interest regarding lead time reduction: input and output of the model, assumptions made and how simplified the model should be (Robinson, 2004).

2.2.4.2 Development of the simulation model

The simulation of a real production needs entities, activities, resources, attributes, logic and global variables. The entity is one of the basic parts of a simulation, they can be seen as objects that you create in order to simulate actual things. An entity could range from an email to a car or service. Activities can be seen as processes in a simulation, if an entity meets an activity it will result in an event. Events occur at specific times and causes the state of the simulation model to change. Resources are the actual places where work will take place or where entities will be processed. A resource can be busy, idle, in waiting mode or down due to failure. Attributes give the entities unique values that describes them, all from colour to size or weight. Logic is used when you want to build logical systems in the simulation model, an instance where it could be used is if you have dependence in the system - as an example: step three in the production cannot be finished or started unless step one and two have been completed. Another important function in the simulation is the use of global variables. Global variables can be reached/changed in any part of the simulation. An example is the use of a variable called Electrical_Power, if you cancel it in one place the use of a global variable would enable you to cut the power to all resources that use Electrical_Power (Ingalls, 2008).

The AutoMod software adds extra possibilities through visualizations as well as a statistical program that can perform several runs of the model. By visualizing the model it becomes more comprehensible for the user. It can also act as a tool for presenting the result to people unfamiliar with simulation as well as the area the model is meant to mimic. The statistical tool AutoStat enables the user to create scenarios where either variables are changed in order to experiment or just to make several runs in an order to find how confident the model is (Banks, 2005).

2.2.4.3 Verification and Validation

One of the most critical parts in a DES is the verification and validation stage of the computerized model; how to do the things right and how to do the right things, respectively. During the development process of this project's DES, a number of different verification and validation techniques were used which are explained in this chapter.

The verification stage of the conceptual model has the purpose of ensuring that the computerized model, has been developed correctly (Banks, 2005; Sargent, 2013). According to Sargent (2013) the user's value of the model is related to the cost of the model. The higher the cost is, the higher the confidence of the model will be. However adding extra confidence in an already costly project is expensive. Another cost related verification technique is to verify new code during the work of the project, this since errors occurring in the beginning of the project is less costly to correct than in the end. That since early errors might trigger a number of new errors in code developed later (Banks, 2004).

Firstly, the authors who developed the code made a plan of how to structure it. The plan was based on the sequence of the different processes and the flow among them (Banks, 2004). In order to make the code easy to read and to analyze; names of entities and loads were given in a standardized way. Through this way a person who is unfamiliar with the project and coding can still get an overview of what is happening in the model (Banks, 2004).

The graphical feature of AutoMod was also used as a verification tool. Using that technique the authors tracked and traced the whole production flow in order to assure that it was correctly represented in the simulation model. At last, the message printing technique was used in order to print predefined messages. The messages can be used to check if the output data correspond to the input data and vice versa (Sargent, 2013).

In the validation stage, the DES base model should be analyzed to check if it corresponds to the real system’s behavior; taking into account the assumptions and level of detail that were used in the simulation project (Banks, 2005; Sargent, 2013). Based on the literature (Banks, 2005; Sargent, 2013) the validation of the DES model can be conducted by using a number of different techniques. Some of them are: Sensitivity analysis, Extreme-condition tests, Consistency checks, Animation, Comparison to Other Models, Extreme Condition Tests, Historical Data Validation, Traces, Turing Tests, Face validation. A number of these techniques should be used in parallel in order to achieve a better validation level of the computerized model.

2.2.4.4 Experimental design

The experimental design includes the different types of losses that have to be identified as well as the selection of what experiments to be performed and the building of an operational model Robinson (2011). The design also need to include: Run time of the simulation, number of runs and the warm up time (Banks, 2004). Lastly the methodology used for finding constraints in the simulation is presented.

2.2.4.5 Operational model

The operational model is the finished simulation model that can be used to develop results based on experiments (Robinson et al., 2011). In AutoMod, the tool AutoStat is powerful during the experimentation phase. The tool enables the user to vary a variable over different simulation runs in order to decide the best value for this variable. For each simulation decisions regarding, warm up time, length of simulation run, and the number of simulation runs can be done.

2.2.4.6 Importance of warm up time

Each simulation starts with an empty production. The time it takes to reach a normal production state should be the warm up time. In the bushing production where there is a 24 hour process the warm up time will exceed 24 hours. If warm up time is used the simulation output will not include the first warm up hours. In AutoStat there is a function which helps the user to determine which warm up time to use (Banks, 2004).

2.2.4.7 Operational model in this thesis

The operational model is the "future" state of the base model. It is used in order to find the optimal combination of variables. The method of how it is done is described in the methodology chapter (Chapter 3)

The operational model will try to answer the following questions:

- How will changes in batch size respectively the setup time of the winding machine affect the production lead time?
- Will the optimal lead time result in a lower production output?

2.3 Toyota Production System

The following subchapter will introduce the basic Lean tools as well as a more detailed description of what Value Stream Mapping is.

2.3.1 History of Lean Production

2.3.1.1 The business environment in Japan

What we today call Lean Production is based on something that has developed over the years and still is in development. The start of Lean Production can be found during the American occupation of Japan after World War II. The domestic car and truck market in Japan desired a wide range of vehicles, all from luxury cars to the government to large trucks that could carry goods and small cars to the crowded cities. At the same time, there were changes made in work regulations, the changes were forced by the Americans. The unions now had to represent both blue collars as well as white collars and less difference was made between them. Some of the strictest work regulations were introduced, it was no longer easy to fire a worker. During this time a separate movement could be noticed; the workers of the companies no longer accepted being seen as an interchangeable workforce that could be replaced as soon as they were worn out. A big difference with the western world when it came to the workforce was the lack of guest workers. The guest workers in the western world accepted lower salaries and made the companies even more competitive. Another difficulty for the Japanese companies were the lack of capital, the war economy were strictly limited and purchases of the latest machines and technologies from the west were impossible. This created an environment which forced the Japanese companies to change, some help regarding the competition was given from the Japanese government since they introduced tolls (Womack et al, 2007).

2.3.1.2 The beginning of the Toyota Production System

In the early 50s the lead production engineer at Toyota, Taiichi Ohno tried to figure out how to meet these difficulties. He had studied the American automakers who had one stamping machine for each part that needed to be made, through that way they saved time on changeovers and could produce parts constantly. However, Ohno knew that Toyota did not have the need to produce as many parts since there were no demand for it. So his solution was to try and use one stamping machine for many different parts. Originally the changeover time for a stamping process was days or even months and it had to be done by dedicated stamping changeover personals. Ohno studied the machines and came up with a clever system which enabled the operators of the machines to change the stamping dies using dies on wheels. Through this way the changeover process could be lowered to minutes instead of days. This technique was later developed into the Single Minute Exchange of Die (described in chapter 2.3.6). The change was a success and when a production of small batches were introduced they immediately saw the benefits of having low inventory. The cost got lower, no need for storing large amount of goods, the quality got higher, a quality error now became more visible since the part would be used within the next hours and not stored for a couple of weeks. This also led to workers that cared about the final result of their work. Even though these improvements were made in the early 50s it were not until the late 80s early 90s that the Americans came to realize that something was going on in Japan. At that time the Americans went to Japan to study the TPS, they liked what they saw and brought some of the techniques back home. After some development by the Americans it was named Lean Production (Womack et al, 2007).

2.3.2 Value Stream Mapping

Value Stream Mapping, is a paper and a pencil tool that is used to create an overview of the flow of information and materials of a production line. An important outcome of the VSM is the observed lead time as well as the total time of value adding activities. The drawing of the current state is usually done by “walking the process” where one measures all the time values by hand, not basing it on data collected through manuals or statistics. A VSM includes the customer demand, the process data of every machine that is utilized, the level of inventory and the material and information flow. In addition, the lead and value-added time between each process are included. The design of the future state is based on a number of factors which are described in a great extension by Rother and Shook (2003). The production capacity of the future state is defined by the real customer demand. In addition, the possibility of implementing continuous and levelled production flow shall be considered for reaching smaller buffers and shorter lead times. The final stage of the VSM is, an action plan of all the improvements that will be implemented. Every change ought to be evaluated before applied; while the implementation process should be done incrementally.

2.3.2.1 Advantages and disadvantages of using VSM

Value Stream Map is a useful tool which has been used for a couple of years for improving a system performance. The main advantage of the VSM is the fast, graphical representation of how information and material flows between multiple supply networks and manufacturing processes, By visualizing the value and non-value adding activities (Khaswala and Irani, 2001). Waste activities can be easily identified and in the same time, respective improvements can be found. In addition, VSM is a great tool to communicate the current and the future state of a system between the management and the blue collar employees (Rother and Shook, 2003). For that reason, VSM is a widespread tool among different sectors which want to become more efficient and effective, such as: manufacturing, IT, healthcare, military.

On the other hand, a number of different disadvantages are described in the literature. VSM can be applied in product families which share the same processes and they can be characterized as "high-volume-low-variety" products. In addition, a VSM does not take into account the space which is allocated in a workshop, for buffering, material handling and/or storage space (Khaswala and Irani, 2001) either the design of a facility. In the VSM, the "value" is not measured, in monetary terms (Nash and Poling, 2008).

Table 2 Advantages and disadvantages of using VSM

Advantages	Disadvantages
Can be created very fast.	Applied only to product families with shared resources.
Representation of information and material flow, using icons.	Applied to "high-volume-low-variety" products.
Visualization of value and non-value adding activities.	Space allocation for storage and material transport, is not considered.
Is useful for identifying the waste activities and possible solutions.	The design of a facility is not considered.
Very good tool for communicating the changes, within an organization.	The "value" term is not described in monetary terms.

2.3.3 Waste in Lean Philosophy

The idea of waste is strongly anchored in the Lean philosophy. In short; everything that does not add value or (products that) differs from what the customer wants is waste. In TPS they split them into three main areas: muda (non-value adding activities), mura (unevenness) and muri (overburden). The seven wastes were defined by Ohno (1988) and tries to describe the term "muda" in a more accurate way.

2.3.3.1 Muda (the seven wastes)

The seven wastes describes activities that are not adding any value to the product itself. Myers (1993) suggests the seven waste should be extended with an eight (unutilized skills) part. This since poor utilization of skills leads to losses in both humans and money.

- Transportation
- Inventory
- Unnecessary motion
- Waiting
- Overproduction

- Over processing
- Defects
- (Unutilized skills)

Of the seven wastes, Ohno described overproduction as the most severe one since it means you produce more products than the market requires. That means that for each product you will experience each of the other wastes like waiting and transportation (Liker, 2004). The wastes relation to production lead time is strong. Each of the seven waste have their contribution to the production lead time.

2.3.3.2 Mura (unevenness)

Unevenness in the production regarding the customer demand is a big difficulty for any production factory. The demand varies over the year but varying the output of a factory is more difficult. The suggested solution is to try and level the production to be equal during all months of the year, in the literature often referred to the Japanese word "Heijunka" (Liker, 2004).

2.3.3.3 Heijunka (levelling the production)

Heijunka tries to prevent three main problems with an uneven production. Liker (2004) describes them through this way. Firstly, an uneven customer demand causes problems if you always produce according to schedule. For instance if you produce large items in the beginning of the week and smaller ones in the end, the order of small ones will take long time to be processed since it has to wait until the large ones have been completed. The solution here is to produce in smaller batches that are spread out evenly during the week. Secondly, producing according to schedule disturbs the resource utilization. Producing large items compared to small ones take different amount of time and might cause stressful production or times where no production is "needed". Lastly, an uneven production causes a bullwhip effect on the suppliers. By rushing the production during time of rising markets or sudden large orders the suppliers have to produce faster and also resupply themselves. This leads to large "bullwhip" effects in the order systems of the suppliers who tries to secure enough raw materials by increasing the orders (Forrester, 1958; Liker, 2004).

2.3.3.4 Muri (overburden)

Misuse of the humans in an organization is described as muri in Japanese. It ranges from having un-ergonomic workstations to workers that are working too hard compared to what is possible. Muri can also be found among the white collar jobs where unused creativity can be one of its results (Liker, 2004).

2.3.4 Work-In-Progress

The Work-In-Progress is closely connected to the "inventory waste" area. Everything in the production that is not yet completed is defined as "Work-In-Progress". This means that products in buffers, in machines everywhere except for the finished products are defined as WIP.

WIP is costly since it ties up capital (through a longer production lead time), large buffers contains a lot of value. Another drawback of a large WIP is that if an error occur, it will take longer time to realize that the fault have occurred since the products need to travel through a large buffer until the error would have been detected further downstream (Liker, 2004).

2.3.5 Just-In-Time

Just-In-Time is one of the Lean tools that have reached many companies. In short, it means that you produce the right amount of products at the right time. According to Shook and Dennis (2007), it is built up of four main areas.

- Production based on customer orders.
- Leveling the production and the demand to create an even flow.
- Create a visual link between customer demand and the production itself, such as kanban cards.
- Enable a flexible production, from machines to operators.

A JIT production is based on the idea that products are pulled through the production rather than pushed. Push production is when you produce according to a schedule based on old customer demand data. This production type often lead to over production or production of the wrong products. Pull production is based on the idea that a customer order is linked to the production itself. As soon as the order arrives it will be linked to the MRP system in order to see if it's producible and if so later put into production when available.

The most famous JIT principle is the kanban system, it is meant to force the organization to use a pull production instead of the more common push production. In a kanban system; cards are used to signal that the production of a certain product can start. The card can be replaced by the refillment of an empty box or an electronic signal that tells the operator that the following process has a spot available for a new product.

2.3.6 Single Minute Exchange of Die

An important tool in Lean Philosophy, is the SMED, it is a clever way of how to reduce the changeover / setup time of a machine. It was developed by Shingō (1985), at Toyota. In order to reach a leveled production one needs to be able to produce in small batches. Between each batch a changeover of the machine has to be done. The SMED is a method for improving the changeover procedure. The SMED is performed through three main steps:

- Firstly, all the tasks that can be performed while the machine is running are identified, those are called external activities.
- Secondly, one studies the remaining internal activities that have to be done while the machine is stopped, the goal here is to transform them into external activities.
- Lastly, everything is reviewed and both external and internal processes are made as efficient as possible. Through this way the changeover / setup time can be reduced by as much as 90%.

2.4 Production lead time and WIP in DES and VSM

In discrete event simulation the production lead time can be traced through a number of different ways. The amount of products in a queue or total amount of WIP is directly related to the production lead time. It is also possible to use one of the counting functions in AutoMod, by appointing a certain start time for a single load and reading it`s time when it leaves the system one gets the lead time (Banks, 2004). Investigating the production lead time is one of the main reasons for performing a VSM. The production lead time is calculated by data from buffers (queues in DES) as well as process times.

The calculation is based on Little's Law formula (eq. 1) which can be explained as it follows:

The lead time equals inventory for each process divided by the throughput for the process following (Szwejczewski and Malcolm, 2013).

$$Lead\ Time = \frac{Inventory}{Throughput} \quad (1)$$

Since the DES is based on a dynamical system, it is possible to study the lead time during different days of the week as well as lead times after stoppages etc. In VSM the lead time represents a snapshot of how the production works in that single moment (Rother, 2003; Donatelli and Harris, 2001).

3 Methodology

In the methodology chapter, the different methods used in order to complete the project as well as the required input for them are described.

The project was built around the question of when DES is preferred over VSM for production lead time reduction as well as finding when DES possible could complement VSM. A case study was performed at ABB in order to find this. Three main objectives were established for the project. Firstly, a complete DES of the bushing production line were performed. Secondly, a complete VSM project was completed in order to get a different perspective of the same production line. Finally, when both of the tools had been completed, the output data were analyzed and a comparison were made, strengths and weaknesses in areas relating production lead time reduction were also discussed. The support needed in order to answer the aims of the project was through creating comparison criterias. The diagram below (Figure 3) represents the sequence of the steps that were followed during the 20 weeks in order to perform this study by the authors.

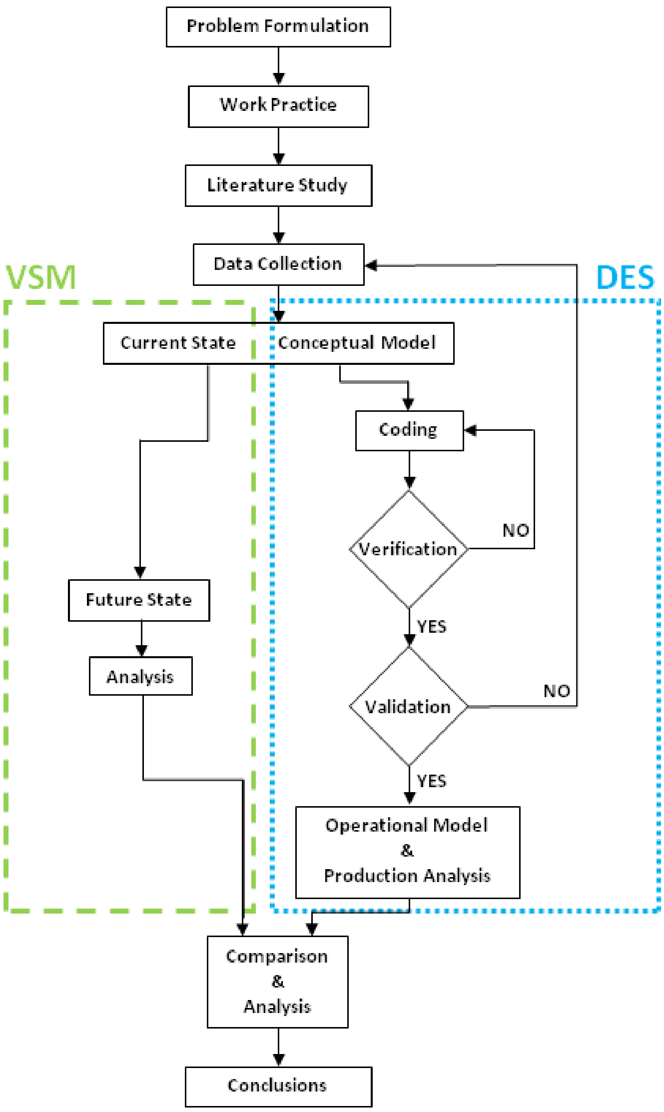

Figure 3 Methodology of the thesis project.

3.1 Project Formulation

A single case study was conducted, in order to fulfill the aims described in Chapter 1. According to Baxter and Jack (2008), a case study can be beneficial when comparing two different methodologies to each other. This approach was selected in order to find if DES and VSM possible are efficient methods for production lead time reduction. The result from an investigation of a real production system provided detailed data from different data collection methods that were used as input in for the DES and VSM tools.

The bushing production facility of ABB Components can be characterized as process oriented. A bushing makes it possible to take 400kV. down to a transformer on the ground without having any electric discharge between the ground and the high voltage part (ABB AB, 2010). This requires a high quality on the bushings. A precise delivery time is, also, a critical factor, since the market is characterized as highly competitive. Since the customers are conservative and the bushings come in a wide variety, it is not possible to produce to stock. Therefore, a reduction of the production lead time is of importance.

The production of an electrical bushing can be divided into four processes. In the first process winding, six different types of oil impregnated transformer bushings (GOB bushing type) are wound. The winding process is supplied by three different kind of raw materials. Rolls of electrotechnical paper are stored both at the fifth floor and next to the winding machine. The aluminum rods that are to be wound with electrotechnical paper are stored next to the winding machine. The last part used in the winding process is the aluminum foil, which is stored in shelves next to the winding machine. The steps of the winding process are the following: Firstly, the machine is set up based on what kind of bushing that will be produced, by mounting the paper on the heater, adjusting the knives and choosing the right type of aluminum foil and inserting the aluminum rod, in the machine. Then the operator winds paper onto the rod, and then the production starts. Aluminum foil is inserted at specific places, by the operator. When the bushing has reached the desired diameter, the winding process is stopped and the product is moved by the operator to an oven, in order to wait until the next process starts. In the assembly process which is the second process, the raw material is taken from a supermarket based on information provided in the order details. The wound aluminum rod is fetched from the tilted oven just next to the assembly area.

The assembly is performed by one operator who is also responsible for the quality of each bushing. The quality inspection is performed via two different methods. The first method, is an optical and haptic control. The operator is using its eyesight and hands in order to check that all parts are set in the right order and in the right place. The second method, is an insulation resistance test by using an Ohmmeter for assuring that the “O-rings” have been connected properly. When the bushing has successfully passed all the tests, the operator puts the assembled bushing in an oil and vacuum process.

The third stage of bushing production is the electrical testing. In the testing area, which is a common area for three different kinds of bushings (GOB, GOH, GSA), an operator test each bushing. Firstly, the operator submerges the grounded bottom of the bushing in an oil tank. Secondly, the operator applies electrical voltage to the bushing in order to test it. If the bushing passes the electrical test, it is forwarded to the next process, packaging; otherwise, it goes back to the assembly process for disassembling where it remains there until the assembler fix the failure or sends it back to the winding process for rewinding.

Finally, at the packaging area, three different kinds of bushings are packed. Standard bushings are packed in quick assembled wooden boxes but non standardized bushings as well as heavy bushings are made in prefabricated heavy boxes. Those boxes requires extra work in form of labeling. The cycle time varies based on which type of bushing that will be packed. When the bushings have been packed, they are stored in an open area outdoors. The packaging area is the last station for a bushing that will be examined, in this thesis report.

3.2 Data collection

The data collection process was divided into two separate parts, firstly, data collection for the DES and secondly for the VSM.

3.2.1 Data collection for DES

The main parameters that were used during the coding of the real production flow were: the bushings production plan, product specifications, arrival time of raw material, cycle times, changeover times, material usage, Mean Time To Failure (MTTF), Mean Time To Repair (MTTR), rework rate and the operators working schedule.

According to Robinson and Bhatia (1995) there are three different categories, regarding the data that are needed for performing a DES:

- Available data (category A)
- Not available but collectable data (category B)
- Not available and not collectable data (category C).

During this thesis, the authors had to retrieve data belonging to the Category A and B and in some cases combined data from different categories. This in order to have high level of credibility (Pegden, Shannon and Sadowski, 1995; Skoogh, 2011).

The following table (Table 3) presents the correspondence between the needed data for the DES and two main categories. The DES data was collected through studying recorded data in archives, through direct observations where the authors studied the processes, through semi-structured interviews which complemented the other methods and through statistical analysis of the recorded data.

Table 3 Data Categorization.

Type of Data	Categorization	
	Category A: Available	Category B: Not available but collectable
Bushings Production Plan		X
Products' Specifications	X	
Raw materials' Arrival Time	X	
Processes' Cycle Time	X	X
Processes' Changeover Time	X	X
Material Usage	X	
Mean Time To Failure (MTTF)		X
Mean Time To Repair (MTTR)		X
Rework Rate		X
Operators Working Schedule	X	

A number of various techniques were used to collect the needed data for the DES. These techniques are described below.

3.2.1.1 Archival Data

A wide range of the data used, were already available to be put into the model (Category A). This since the company has a specific procedure for documenting each product requirements. Mainly, the data for the DES were extracted by the Enterprise Resource Planning (ERP) software. The software provided precise and accurate data on the arrival time of raw material and material usage. Regarding the cycle and changeover time of the winding process; a recording made by an operator in the past acted as a precise information about how long time it took to wind each type of bushing. The data was recorded precisely by timing the span between the start and stop of the work process. Through this way samples based on one year's production were analyzed based on the average values of the data.

3.2.1.2 Direct Observation

During the first week of the project a work practice took place for gathering the "not available but collectable data" (Category B). The practice was done according to the 12th Business Principle of Toyota Production System; Genchi Genbutsu - Go & See (Liker, 2004). The authors spent one day at each production station in order to get a better understanding of both the flow as well as the difficulties of the production. A valuable outcome of a work practice were the hidden insights that the operators might have about how things work in "reality". The work practice was performed in cooperation with the operators who answered questions as well as showed the processes thoroughly. The data was gathered by keeping notes and using a stopwatch.

3.2.1.3 Interviews (semi-structured)

The bushings production plan, in distribution terms, had to be collected, this was mainly done through analyzing archival data (Category B) of how the distribution of different bushings appeared during the year. Complementary semi-structured interviews with the manager of the production planning department, production engineering department and the workshop supervisor were also made in order to ensure the validity of the data. The semi-structured technique was selected because it gives flexibility to the interviewees and the interviews to reflect upon the specific topic and also expand on other topics which could be important for further investigation (Wilson, 2014). The same interviewing technique was used by the authors, for calculating the frequency of the rework rate. In this case, the senior production engineer was interviewed. The Interview Guide which was based on Wilson (2014) can be seen in the Appendix A.

3.2.1.4 Statistical approach

A goodness-of-fit test has been performed in order to select the statistical distribution of the input data. This has to be done in order for the DES model to recognize the data. (Banks, 2004; Banks, 2005; Leemis, 2004; Helander, 2009). According to Dodge (2008), the goodness-of-fit test, can be done either manually or through a statistical software in order to find if the selected distribution fits the data. Kolmogorov-Smirnov and Chi-square are two of the most used methods for goodness-of-fit test. In this thesis, the authors used the statistical software JMP (SAS Institute Inc., 2009), for the Chi-square goodness-of-fit test (Banks, 2005).

In the computer program the user receives how well the data matches a range of different distributions. In order to be able to use the data in AutoMod one needs to use one of the distributions available in the program. AutoMod supports normal, exponential, triangular, weibull, poisson, binomial, lognormal and gamma distributions (Banks, 2005). During the development of the DES computerized model the following distributions were used:

- The normal distribution can simulate symmetric random variables. Since the values can become negative it is important to be careful when using it. The normal distribution is commonly used to simulate process times and repair times.
- The exponential distribution creates values of a wide range. It is often used to simulate the time between single events.
- The gamma distribution is a flexible function which can model non negative random variables. It is commonly used to simulate random process times and down times for processes.
- Weibull is a powerful distributions since it can mimic the attributes of a wide range of distributions. It is therefore suitable for data where it is difficult to find an accurate distribution. It is often used in reliability models to simulate the lifetime of objects.
- The triangular distribution creates a range of values between a minimum value, a most likely value, and a maximum value. The distribution is suitable for simulating human task times such as manual assembly (Banks, 2004).

In this project, triangular distribution was used in order to estimate the cycle time (Category B) of the electrical testing process, based on an interview with the operator.

3.2.2 Data collection for VSM

The data in a VSM project is mainly collected on the shop floor. The guidelines from "Learning to see" (Rother and Shook, 2003) are to collect: cycle time, changeover time, setup time and inventory levels. Other data that needs to be found are: number of shifts, uptime of each process, batch size, number of operators, customer demand and how the information flows.

Following to suggested procedure of Rother (2003), value stream maps are performed by teams that should represent the area that is to be investigated. The VSM were performed by the two authors, the production planner, the workshop manager as well as a production engineer from a different production line. Originally, the idea was also to include one or two operators (which would have made the team complete) but due to certain reasons they could not join.

3.3 Validation

In order to get high quality of the results, the validation process was divided in two parts: the first one includes the data validation for the DES base model and the second; the data for the VSM current state model. The validity of the data used in the base model was decided through two different techniques, face validation and sensitivity analysis.

The face validation technique (Banks, 2004; Banks, 2005; Sargent, 2013; Helander, 2009) is based on the involvement of people with deep knowledge of the actual system and how it is performing. For that reason, the supervisors of the examined production system were asked to examine the results continuously during the development process of the DES base model. In addition, a sensitivity analysis of each building step was performed by the modelers in order to make sure that changes in the input data affected the output in a predetermined manner.

The validation of the VSM data was conducted by the team who mapped the production flow. The data was collected either through stopwatch, counting and unstructured interviews with operators and between the team members.

3.4 Experimental method

The methodology used while investigating improvements in the simulation model was the theory of constraints which was an outcome of the book "The Goal" (Goldratt et al, 2004). It describes a methodology of how to continuously identify constraints of a system. The methodology is based on the five steps presented below:

1) Identify the constraint.
2) Investigate how the constraint can be used as effectively as possible.
3) Subordinate other resources to help the constraint.
4) Elevate the constraint (for instance adding extra capacity to it).
5) Identify the new constraint by moving to the first step.

The constraint is often referred to as the "bottleneck" of a system. In this thesis the TOC methodology have been used while creating the operational model of the DES.

3.5 Comparison of DES and VSM

DES and VSM are two different tools that can be used for describing, analyzing and evaluating production lead times. There are a number of comparisons between the two tools in the literature. According to Mahfouz et al (2011) the DES can be considered superior to VSM regarding accuracy if a proper verification and validation have been performed. Xia and Sun (2013) state that due to the fact that the simulation model is functioning in a dynamical way it results in that it is less affected by assumptions made by the users of the VSM. In addition, the accuracy of VSM is still an area with potential improvements, even if, a number of complementary tools to VSM have been developed (Singh et al., 2011).

In the project, different methods were applied in order to compare DES and VSM. The result will be used in order to answer the two aims; when is DES preferred over VSM for production lead time analysis and if DES could complement VSM in such an analysis? The comparison criterias are presented in Table 4 below.

Table 4 Comparison criterias from DES and VSM.

Time to perform	The time it took to perform each tool was recorded by noting the number of weeks and days it took to perform them.
Competence needed	The competence needed was decided by analyzing what kind of background knowledge that was needed for each tool.
Data availability	The data availability for each tool was rated by the time it took to find the data and if the data needed to be processed.
Accuracy	The accuracy in this project is defined as how close the calculated production lead time came to the production lead time supplied by the computerized ERP system which kept an updated record of each bushings production lead time.

4 Results and Analysis

When both the DES and VSM have been created the results are analyzed and compared. Main focus of the results are the possible effects on the production lead time and how DES could complement VSM.

4.1 Presentation of production lead time

In the DES model, the production lead time is recorded in a table which collects the production lead time for each bushing. The table is summarized as a result screen showing, average lead time, mean lead time, and the standard deviation. In the VSM, the production lead time and the process time are presented for each buffer and process, respectively, as well as the whole flow. The VSM tool presents the production lead time in a more intuitive way where it can be clearly seen the station has the largest effect on the production lead time.

4.2 DES base model results

The chapter below presents the results from the base model of the discrete event simulation. The base model results show what the production looks like before any changes have been made. Each simulation run was repeated through five different runs, this in order to minimize the variances of the results. A warm up time of five days was used based on the fact that it took five days for the level of WIP in the queues to flatten out.

4.2.1 Simulation results

The table (Table 5) below shows the simulation results of the base model. As it can be seen, the average production lead time is 5.05 days and the average production output is 11509 bushings.

Table 5 Base Model results.

Output	Production Lead - Time	Production output
Average	5.0494	11509.0
Std. Dev.	0.0152	68.407
Minimum	5.0186	11360.0
Maximum	5.0751	11562.0
Median	5.0617	11552.5

According to Robinson (2004) the conceptual model (Figure 4) of the examined production line was created and that was the base upon which the model was built. The flow can be seen as well as number of operators, and the number of processes. In total, it took four weeks to finish the base model, including the verification and validation of it.

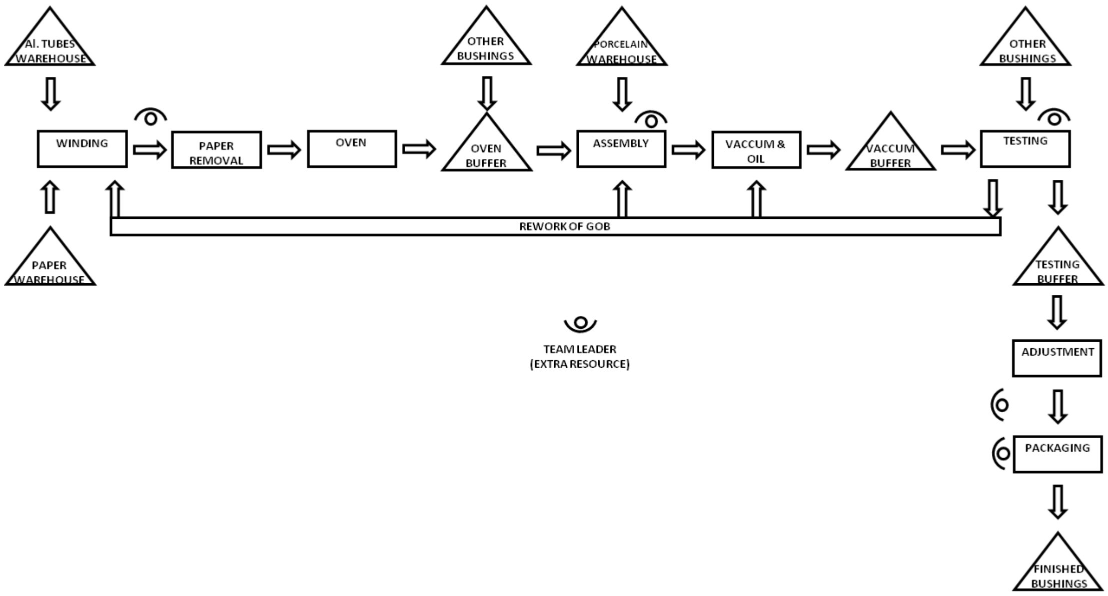

Figure 4 The Conceptual Model.

4.3 DES operational model results

The following questions were used in order to investigate the parameters that affect the production lead time:

- How will changes in batch size respective paper setup time affect the production lead time?
- Will the optimal production lead time result in a lower production output?

This scenario was simulated using a multivariable analysis in AutoStat. Two variables were used, one that controlled the batch size and one that decided which set up time to use on the winding process. The batch size was varied from 1-4 with incremental steps of one. The paper setup time for the winding machine was varied from 20 - 60 minutes with incremental steps of five minutes. The reason that the paper setup time was chosen to be varied is that the only way to reach a mixed production is through performing more set ups on the winding machine - thereby producing different types of bushings more often. The combination of the different factors leads to a total of 175 runs, where each combination was repeated five times in order to minimize variances. The building and analysis of the operational model took four weeks to finish.

4.3.1 Simulation results

As can be seen in figure 5 below, the production lead time varies between 1.4 and 3.2 days for the different batch sizes and setup times. In figure 5 it is also possible to see that the production output and the production lead time behaves similarly for the different batch sizes and setup times. Whenever the batch size is increased the production output and production lead time is increased.

Another trend that can be seen is that at larger setup times the lead time is reduced for the different batch sizes. This can be explained by the fact that the longer it takes to set up the winding machine the more the winding machine becomes the bottleneck and when the rest of the line is starved. Therefore the bushings hurry though those processes without much waiting time and the production lead time is reduced. In figure 5, the two vertical axes shows production output on the left and production lead time on the right. The horizontal-axis shows batch size and setup time.

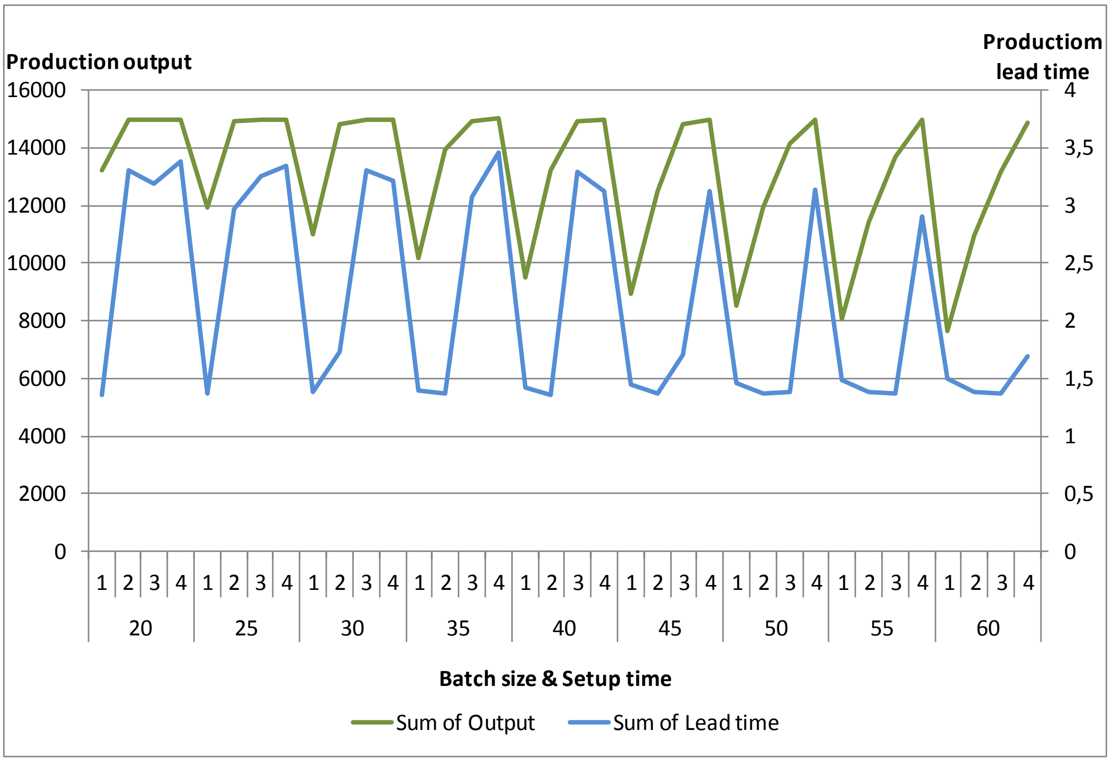

Figure 5 Production output and production lead time depending on batch size and setup time.

4.3.2 Production Output depending on batch sizes and setup times

The results below present the output and how it varied with different batch sizes and setup times. Output is on the Y-axis and batch size/setup-time is on the X-axis. As can be seen, the output is dependent on the batch size that is used. A small batch size lowers the output and a larger one increases it. A lower setup time acts as a counterweight to the losses that the smaller batch sizes creates.

In Figure 6, the repeating numbers 1-4 represents batch sizes, corresponding bars shows the varying output for respective batch size when the setup time varies from 20 to 60 minutes. The blue lines shows the production output for the respective batch size(1-3) and its relation to the setup time.

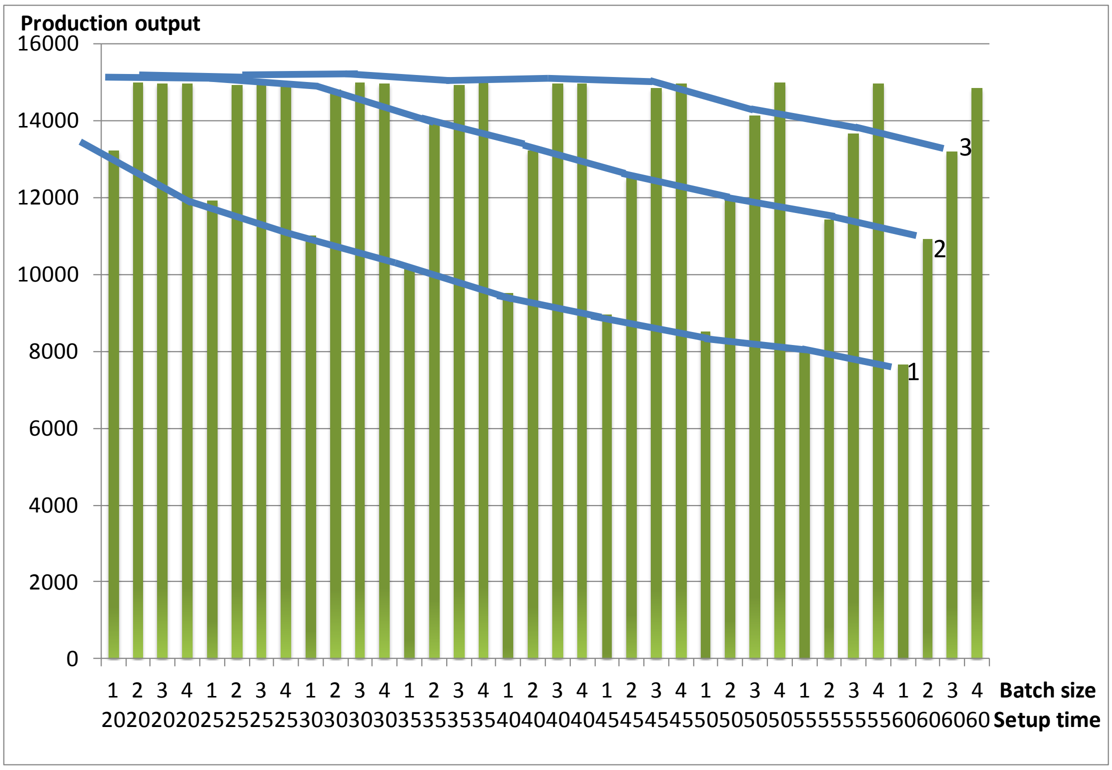

Figure 6 Output depending on batch sizes and setup times.

4.3.3 Operational model summary

The production lead time is affected by both the setup time and the batch size. A small batch size generally leads to a lower production lead time. The different batch sizes and set up times presented a wide range of production lead times. As an example, a batch size of one and a setup time of 30 minutes led to a production lead time of 1.5 days. Which is 70% smaller than the previous production lead time of the base model which was 5 days. This, however, led to a drop in the production output. A batch size of two and a setup time of 35 minutes led to a production lead time of 3.1 days and a sustained output of 11500 bushings. This is a reduction in production lead time by 38%. The results from the operational model shows the strengths of a DES. By investigating a large number of different combinations, it is possible to find the optimal combinations for reducing the production lead time while still maintaining the production output.

4.4 VSM current state

The current state of the analyzed production system can be seen in Appendix B. The map is divided into two parts. The upper part contains the information flow, which includes information from customers, the suppliers and to the processes. The lower part graphically represents how the material flows, from the different suppliers to final customers, through the buffers and the processes for three product families. In addition, the production lead time and the process time has been calculated for each buffer and each process, respectively. Since the testing and the packaging processes of the examined production line are shared between the different products, different production lead time and process time have been calculated. In total, the current state of the VSM took five days.

Based on the current state of VSM, the total production lead time of the GOB production line is 9.39 days. In the VSM, it can be directly seen each processes contribution to the production lead time. The buffer and the cycle time of each process results in a local lead time and in the end all of them can be summed up to a total production lead time. In the current state of VSM, the winding machine has the largest contribution to the production lead time (7.09 days) which can be explained due to the large amount of metal rods that are waiting to be wound. Among the wound bushings which are waiting in the production line, the vacuum and oil process has the largest contribution due to the long process time that takes place in batches.

The following table (Table 4), summarizes the total Value Added Time of each product which is the quotient of the division among the process time and production lead time.

Table 6 Value Added Time for each product family, of the current state.

Product	Value Added Time [%]
GOB	10.98
GOH	20
GSA	5.5

Overall, the current state of the VSM graphically represents how the production lead time is distributed among the different processes. Thus, it gives an indication about the possible improvements that could be implemented that would lead to a decrease of the production lead time.

4.5 VSM future state

The next step after the creation of the current state map of the production system is the development of the future state of it. One of the most applicable methods for a successful creation of the future state map is by answering eight questions that helps the user to find areas of improvement (Appendix D) Rother and Shook (2003). The making of the future state model including analysis took three days.

4.5.1 Changes in the Inventory Level

As it can be seen, in the map, there is a huge inventory of aluminum rods which are available to be used in the winding process. An inventory of two week production has been chosen for preventing the lack of raw material. With a safety stock of one week, a better inventory turnover can be achieved along with a better utilization of the workplace. This solution that would reduce the winding machine lead time from 7.09 to 2.91 days.

In addition, a reduction of 20 GOB bushings in the buffer level before the assembly process can lead to a reduced production lead time by 52 per cent.

4.5.2 Changes in the Process time

According to the real customer demand (1140 bushings per month) and the available working time (1155 minutes), the takt time is 21 minutes for each bushing.

The current map of the production flow reveals that almost all of the processes are balanced regarding the takt time, except from the winding process and the packaging process (for the GSA bushing type).

The winding process has a process time of 24 minutes. The bushings are produced based on the received orders and the paper size, in a batch of five products. The bushings are wound according to paper size, from larger to smaller.

A levelled production schedule along with a batch size of 1-3 and a reduction of the changeover time by 10 minutes have multiple positive results. It reduces the production lead time and increases the flexibility of the organization as well as creating a smoother flow (Liker, 2004). The following table (Table 7) presents, an example of a daily and leveled production plan which can be used in order to meet the demand.

Table 7 Mixed Production Plan.

Bushing Type	325	550	450	250	380	650(1)	650(2)	Total
1	15	9	7	2	2	4	1	40
2	15	9	7	3	1	3	2	40
3	14	9	7	2	2	5	1	40
4	14	9	8	2	1	4	2	40
5	14	8	9	1	2	4	2	40
Total	72	44	38	10	8	20	8	200

The creation of the suggested mixed production plan was based on the following pattern:

- The number of the working days per week was calculated, based on the working policy of the company. The examined facility was operating five days per week.
- The average number of bushings per type and week was calculated, according to the customer orders of the last five months. There is a customer demand of 200 bushings per week.
- The total market demand of bushings was equally divided among the five working days, in order to achieve a well-balanced and mixed production schedule. That led to the result that 40 bushings per day have to be produced.
- The number of the bushings that have to be produced was distributed in each working day, manually.

In the packaging process the cycle time in this case exceeds the takt time for three minutes, even if, the two operators are working in parallel. A reduction of three minutes in the packaging process, will result to a total process time of 21 minutes which is a small improvement.

Overall, all the changes above could reduce the total production lead time from 9.39 to 4.9 days. The future map of the production system can be seen in the Appendix C.

5 Discussion

In this chapter the results of this study are discussed further. In addition, possible improvements regarding the way that the study was performed are presented as well as number of recommendations to the company are discussed.

5.1 Summary of the results

The aims were to investigate in which situations it would be preferred to use DES for production lead time reduction rather than VSM and in which situations DES could complement VSM. The results clearly show that for a production with many variables and product families; the DES is the preferred option. This since it both enables the user to find an accurate result as well as the optimal combination of variables such as setup times and batch sizes. The VSM is a good tool for getting a fairly accurate overview of the production lead time in simple production environments with fewer product families and cycle/setup times that do not vary. The time it took to perform the two methods varied a lot. The total time for DES including base model, operational model and analysis was 40 working days. The total VSM was finished in 8 days which was 28 days shorter than the DES. The time difference can partly be found in the time spent on finding qualitative data which was time consuming for the DES. The competence needed differs a lot between the two tools. DES requires competence within computer programming and statistical analysis. The authors had previously attended the 8 week course “Simulation of Production Systems - MPR 271” (7,5 credit) at Chalmers University of Technology. To perform a VSM the user needs to understand the basics of the Lean Philosophy as well as understanding what a VSM is. Compared to the DES it is possible for most people to read a guide in order to perform a VSM. There are possible complementary effects between the two methods. By adding the dynamical traits of DES to the VSM, the results gets more precise and can effectively be communicated through the VSM “language”.

Table 8 Comparison of summarised results.

Comparison Criterias	Discrete Event Simulation	Value Stream Mapping
Time to perform	40 days	8 days
Competence needed	8 week course in “Simulation of Production”, 7.5 credits	Basic knowledge of Lean Production and VSM
Data availability	It is time consuming to find accurate data	The data needed in the VSM is easy to find
Accuracy	Accurate if built accurately with high quality data. 5.05 days production lead time compared to 5.13 (ERP)	Fairly accurate, good overview. 9.39 days production lead time compared to 5.13 (ERP)

5.2 Result accuracy of production lead time reduction

As can be seen in Table 9 the DES shows signs of being the more detailed tool. The level of accuracy in a DES model is based on the quality of the data as well as the time spent on building the model. In this project, the quality of the data was considered high by the authors and there was sufficient time for building a precise model. The existing literature also supports this. Mahfouz et al (2011) concluded that a DES produces accurate results due to its dynamical traits. The accuracy of a VSM depends on when it was performed, how much time that was available as well as how professional the users were. In this project, the time to perform the VSM was enough but due to bad timing it was performed when there had been a previous stop on the production line with a bit skewed data as a result. Another VSM trouble is that, it was performed during the summer when the production rate is lower than usual. This fact was also expected since the literature state that a VSM project might happen during times that are not as representative as usual, such a breakdowns or other sudden changes (Forno et al, 2014). Since the improvement suggestions from the VSM and DES have not been implemented in reality it is difficult to state if the results are true or not, these results can only act as hints. In order to test the validity of the results, the suggestions from the DES and VSM should be implemented and analyzed further. A comparison with the results in this thesis could then be used to verify if the comparisons are valid.

In Table 9, the DES and VSM values for the production lead time are compared to the average value of one year's production lead time calculated through the ERP system.

Table 9 Production lead time for VSM and DES compared to the average value of a yearly production.

Discrete Event Simulation	Value Stream Mapping	Average production lead time
9.39	5.05	5.13

5.3 Usefulness of DES and VSM for production lead time reduction

The two methods are very different related to the time it takes to perform them. In short, the DES is time consuming but can potentially lead to better accuracy. The VSM is a quick method which can be inaccurate but might give a good overview to start with. In the end, the accuracy of the production lead time data will be given by the amount of time spent into finding it.

5.3.1 Analyzing and reducing production lead times through DES

DES can be a powerful tool for reducing the lead time of a production system. A key factor of the DES is the quality of the used data. If the input data is good, a DES has the ability to present accurate production lead time data. DES also has a great advantage when it comes to experimenting. The simulation performed in this project clearly showed that, through the many simulation runs it could be decided which batch size to use and which set up time that was needed in order to reach different production lead times. This shows how powerful DES can be in production environments with large amount of product families and varying cycle times. Lastly, the fact of finding the optimal combinations of variables helps in creating consensus of which improvements to implement, something that saves time.

On the other hand, there are a number of weaknesses which have to be considered. The DES is time consuming and it requires an experienced user both in the creation of the model and in the analysis of the results. In order to get enough data of good quality to put into the model a large amount of time have to be put into finding data. The data also need to be transferred into data that the model can use, such as fitting the data to a statistical distribution. It is therefore a more costly tool. Another disadvantage of the DES is that it is not established within the industry. Many people do not know what it is and might not trust in the results. DES can also be misleading, the results provided by the simulations are very precise and it might give a false feeling of accuracy.

5.3.1.1 Typical situation when DES is appropriate

The user wants an accurate overview of the production lead time of a production system that contains one or more product families and production lines. The complexity of the system can vary - the more complex the more time consuming. The time and money available should also be sufficient.

5.3.2 Analyzing and reducing production lead times through VSM

The VSM tool is a swift tool for finding the production lead time. If it is done in a correct way and during a time when the production is not disturbed it can also be fairly accurate. It is a tool that can be performed by people with little training on the subject and it is often done in educational purposes. The actual visit at the workshop is also a great benefit of the VSM tool. By watching the production it is possible to learn how it really works. The data needed in order to complete the project is most often easily available. Most of the data needed is collected at the production line by hand. Another advantage is the visual presentation of the results. Many people are familiar with it and the industry have used it for quite a long time by now. Therefore he trust is high. Another advantage with the VSM procedure is that it includes hints of which improvements to investigate, through answering the 8 questions the user gets an idea of which areas to investigate. For instance in the project the 8 questions lead us to introduce mixed production as well as investigating reduced setup times for the winding machine. Lastly the VSM has the advantage of speaking the common language of many people in the industry, the way the results are presented are familiar to many which helps the communication. The VSM performed in the case study helped in reducing the production lead time with 47.8%. But if examined closely the reduction can be mainly traced to the large reduction in the buffer for the winding machine which is a raw material buffer and it could be debated whether it is a “bushing” or not. The implementations of mixed production and reduced setup times only had marginal impact on the production lead time which is of strong contrast to the findings in the DES model.

As with the DES the VSM have a number of disadvantages to be considered. If the VSM was performed during a time where the production was disturbed the result will be affected, something which happened in the case study. Another disadvantage is the inaccuracy, since it is a snapshot it has difficulties in catching the fluctuations of the production flow as well as the production lead time. The inaccuracy of the VSM makes it difficult to find and experiment with possible improvements.

5.3.2.1 Typical situations when VSM is appropriate

The user wants a fast overview of what the production lead time is, the production line and product family should not be too complex and the need for accuracy should not be too important. The same is true for production lines where the data available is limited. If the company is relatively new to the lean philosophy the VSM project could be performed in educational purpose.

5.4 Possible benefits of complementing VSM with DES

A VSM alone shows a static view of a production line. The implementation of a DES in the VSM would enable the user to find answers regarding the dynamical traits of the production system. In the case study, the DES presented how the production lead time was affected by different batch sizes as well as different setup times for the winding machine. That knowledge would not be given by the VSM alone. However, through the way that the VSM is performed it helps in finding areas to improve, those suggestions are preferable examined in a DES. The DES would then help in creating consensus of which improvements to implement. The help in creating consensus also affects the time it takes to analyze, if a consensus can be reached faster it also means that the implementations can be reached faster. This prevents the users to be paralyzed by a never ending analysis of which improvements to make. The production lead time should still be presented in the traditional VSM way where a total production lead time is presented as well as a value adding time. This since those results acts as a common language within the industry and is understood by a wider range of people. By using the tools in such a way it is possible to narrow down the gap between them and make them a powerful tool in cooperation.

5.5 Improvements regarding how the projects was performed

There are a number of possible improvements of how the study was made that should be presented. The timing of when the VSM was performed was not good, which lead to inaccurate results. The merging production flows created difficulties in the DES and VSM. A recommendation is to focus on single flows in order to both present the results in a more comprehensible way as well as not risking to get programming errors in the DES model. It is something that increases the complexity of the model.

Another improvement regarding the project is the data collection of the break down data. It could only be retrieved for the winding machine which created uncertainty regarding breakdowns in assembly, vacuum and oil, testing and packaging.

5.6 Further Recommendations for the case study company

During the work practice it was noticed that the uneven quality of the electrotechnical paper rolls caused the setup time of the winding machine to vary quite a lot. This needs to be investigated in order to reduce the setup time. In cooperation with a SMED project a setup time reduction is very much possible.

The introduction of work rotation, as a way of reducing the production lead time should be further investigated and analyzed. By this way, a better communication can be achieved among the blue collar employees as well as enabling them to help each other whenever needed.

A case study could be performed in order to verify and validate the findings of this project as well as the suggested methodology for the cooperation of DES and VSM tools, in a multiple industrial environments.

6 Conclusion

In the conclusion chapter the aims are answered in short.

"When is DES preferred compared to VSM for production lead time reduction?"

- The use of DES rather than VSM is preferred for calculating production lead times in production systems with many product families, such as the production in the case study.
- In situations when the accuracy is important the DES has the advantage over the VSM, the accuracy of the DES enables the user to come up with the right combinations of variables such as optimal cycle times and setup times. This is something that is clearly shown in the results.
- Since DES considers the dynamical traits of the production system it is helpful when the system is to be analyzed, It helps in creating consensus of what changes that are worth making as well as presenting what sort of variations that the production system experiences.
- DES makes it possible to analyze different scenarios dynamically in order understand what their effects are to the production system, which was clearly shown in the case study. Investigating scenarios in VSM is possible but often time consuming.
- DES enables the user to simulate changes without implementing them, something which can be expensive in many production environments. Simple changes can be investigated in VSM but more extensive ones would be time consuming or impossible.

"How could DES complement VSM?"

- Presents dynamical version of the production system.
- Help in choosing which improvements to implement.
- Makes the implementation of the future state suggestions faster through help in creating consensus of which improvements to implement.

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Appendix A - Interview Guide

<table>
<tr><td>Activity</td><td>Question - Comments</td><td>Time</td></tr>
<tr><td>Introduction</td><td>Short brief of the participants
Introduction of the interviewers
Explanation of the purpose and goals of interview
Revision of the interview method, the future use of data and confidentiality issues</td><td>5 min</td></tr>
<tr><td rowspan="4">Structured Topics</td><td><u>Session 1</u>:
Could you describe the production plan of this line?
Could you explain a bit more about the running time of this line?
Do the operators work in shifts?
Tell us about the average number of the bushings that produced in a daily and monthly base?</td><td rowspan="4">20 min</td></tr>
<tr><td><u>Session 2</u>:
How do you feel about the quality of the input data?
What is your opinion about the DES output data?
Do you recommend us to investigate some other area?</td></tr>
<tr><td><u>Session 3</u>:
Tell us about the bushings that need rework.
Could you explain more about the route of a bushing that needs rework?
Could you describe the route of a reworked bushing?
Could you tell me how often do you have to rework a bushing?
How many of them have to be disassembled?
How many can be fixed without extensive repair?</td></tr>
<tr><td><u>Session 4</u>:
Tell us about the electrical testing process.
Could you describe a bit more detailed that process?
Could you explain more about the setup activities and about the setup time for each bushing?
Could you tell me what is the maximum testing time of each bushing?</td></tr>
<tr><td colspan="2">General questions and open dialogue with participant</td><td>15 min</td></tr>
<tr><td colspan="2">Closing comments and completion of any paperwork</td><td>5 min</td></tr>
</table>

Appendix B - The Value Stream Mapping, current state

The current state of the VSM has been removed due to confidentiality.

Appendix C - The Value Stream Mapping, future state

The future state of the VSM has been removed due to confidentiality.

Appendix D - Eight questions for designing the future state of a VSM

1) What is the real customer demand? What is the takt-time?
2) Will we produce for direct delivery or to a finished goods stock (supermarket)?
3) Where can we produce in a continuous flow?
4) Where do we place supermarket pull systems (buffers) for regulating the flow?
5) Where in the flow will we plan the production (pacemaker)?
6) How do we level the production mix?
7) In which batch size should we produce?
8) Which process improvements are needed (training, reductions of disturbances, quality improvements, reduction of changeover time etc.)?