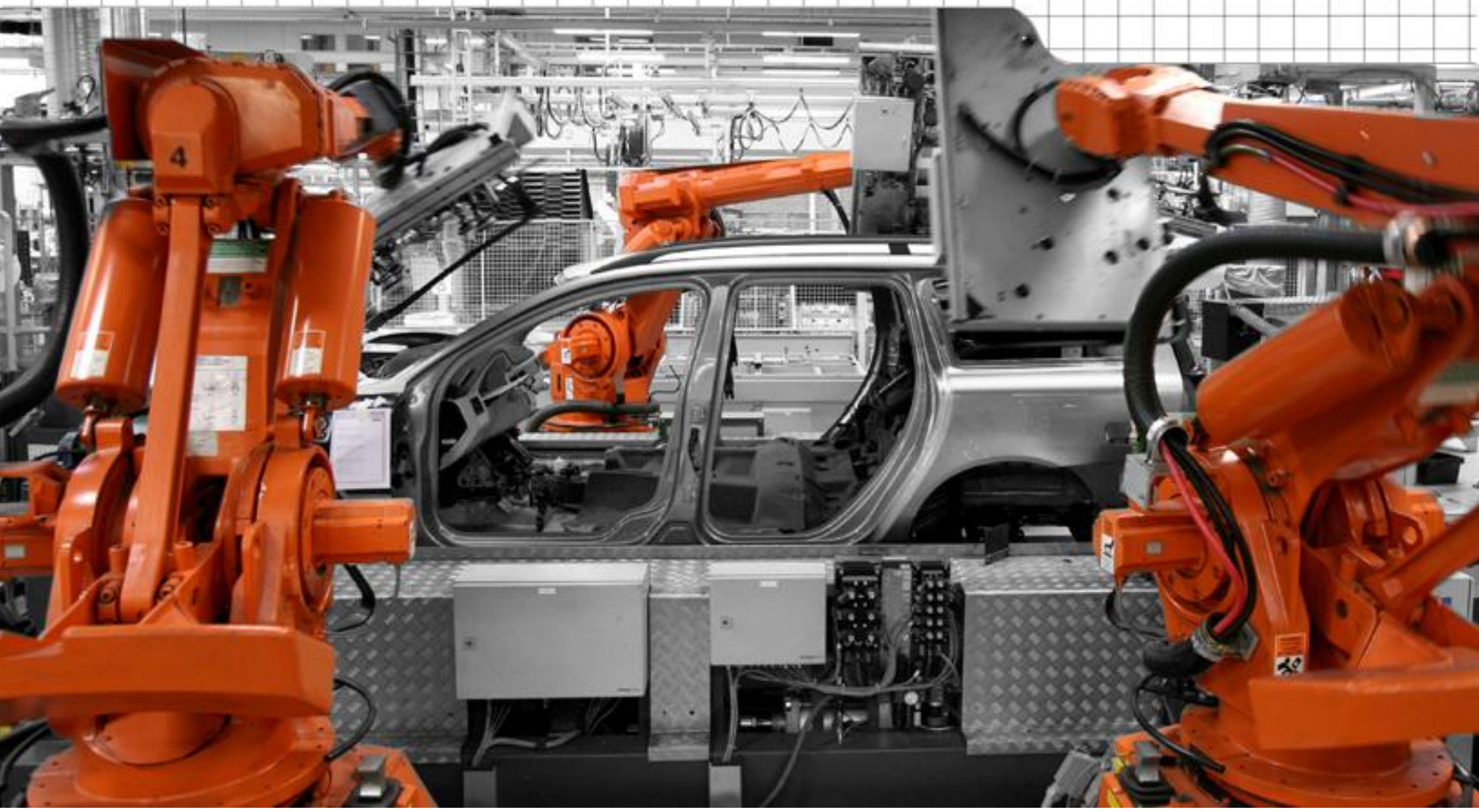

Analysis of System Losses

Capacity Study at Volvo Cars Torslanda

Master of Science Thesis

JESSICA ANDERSSON
MOA DANIELSSON

Department of Product and Production Development
Division of Production Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2013

Analysis of System Losses

Capacity Study at Volvo Cars Torslanda

JESSICA ANDERSSON
MOA DANIELSSON

Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2013

Analysis of System Losses
Capacity Study at Volvo Cars Torslanda
JESSICA ANDERSSON
MOA DANIELSSON

Department of Product and Production Development
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
The cover picture illustrates one of the stations in the body shop at Volvo Cars Torslanda.

Reproservice, Chalmers
Gothenburg, Sweden, 2013

ABSTRACT

This report covers a master thesis work performed at Volvo Cars Torslanda in cooperation with Chalmers University of Technology. The aim of the project was to investigate the different causes of the low capacity and high variability in the production output in a limited part of the body shop. The results of the thesis point out where improvements should be made, and concludes that a possible increase in production output by 9% could be reached. Tools such as process mapping and flow simulation have been used with the purpose of finding the largest constraints in the production system. In order to locate the constraints of the production system initial static analyses were performed, including a process mapping and analyses of historical data. However the initial static analyses were not sufficient enough in finding the bottlenecks, so the project carried on with simulation modelling.

During the project several bottleneck detection methods have been applied and evaluated. The shifting bottleneck detection method was proven to be more successful than both the modified static waiting time method and the utilisation method in this particular case. The shifting bottleneck method resulted in the discovery of a primary bottleneck station as well as secondary bottlenecks. Further experiments, performed in a simulation model, concluded that a synergy could be achieved by combining improvements of a secondary bottleneck, the pallet transporting the products, with improvements of the identified primary bottleneck station.

Keywords: discrete event simulation, process mapping, bottleneck detection.

ACKNOWLEDGEMENT

The authors would like to thank Chalmers University of Technology and Volvo Cars Torslanda for enabling such an interesting master thesis work. The experiences gained by applying theoretical knowledge on a real world production are very valuable. Many thanks to all people who have been involved in making this master thesis successful and especially to those who have spent time explaining and discussing today's production system during the project.

The authors would also like to thank Jon Andersson, who has supervised the master thesis, and the examiner Anders Skoogh at the department of Product and Production Development at Chalmers University of Technology for all of their guidance and support.

Finally, special thanks to Jacob Ruda at Volvo Cars Torslanda who have been a great asset and exceptionally helpful when supervising the project. Without his excellent supervision the project would not have reached such good results.

TABLE OF CONTENTS

1. INTRODUCTION

This master thesis work was performed at Volvo Cars Torslanda, hereafter referred to as "VCT", in cooperation with Chalmers University of Technology. The goal of the project is to study the capacity problems at VCT, as a step towards optimising the production of Volvo cars. VCT produces six different car bodies on the same flexible line in the body shop. In a specific area of the body shop, where the main flow merges with three sub flows, VCT experiences a lower capacity than expected due to system losses. A description of VCT's production plant is given in chapter *3. Factory description*.

This master thesis, hereafter referred to as "the thesis", aims at identifying possible causes to the system losses by using tools as process mapping and flow simulation of a chosen area in the body shop. In this introductory chapter the background to the thesis, section *1.1 Background*, will be described together with the aim of the project, section *1.2 Aim*, the problem formulation, section *1.3 Problem formulation,* as well as the delimitations in section *1.4 Delimitations*.

1.1 Background

VCT produces the Volvo car models V60, V60 hybrid, S60, S80, V70, XC70 and XC90. These, with the exception of XC90, are produced on the same flexible line in the body shop, which makes the process complex. Today the maximum theoretical capacity is never reached and the body shop faces high variability with an average output of about 38 bodies per hour.

In the production flow between the under body buffer, which experiences an utilisation of 80-100% nearly half of the time, and the K10 buffer, which experiences an utilisation of 0-20% nearly half the time, see figure 1, VCT experiences a lower capacity than expected. With a takt time of 60 seconds a maximum theoretical capacity of around 54-56 jobs per hour (JPH) should be reachable. Especially since the area is not limited by the preceding and subsequent production, considering the large initial buffer which is well stocked and the final buffer which appear to be starved. However, the buffer situation does indicate a problem within the area between these buffers.

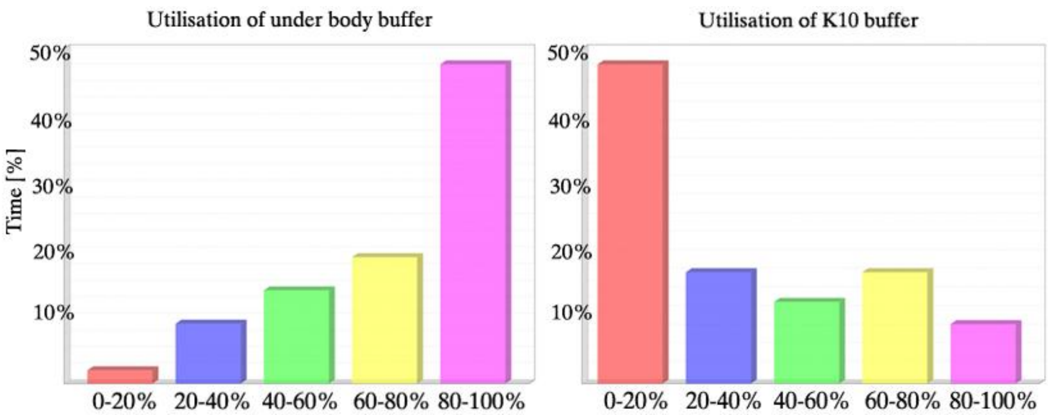

Figure 1, the preceding and subsequent buffers indicate a problem area within the body shop.

The geographical area between the two buffers, which is marked in figure 2, reaches from the large under body buffer downstream to the second buffer, named K10. In the initial under body buffer approximately 80 under bodies are stored and in the K10 buffer approximately 20 car bodies are stored, in wait for further assembly. With regard to these two buffers the system can be considered more or less independent within the marked area in figure 2.

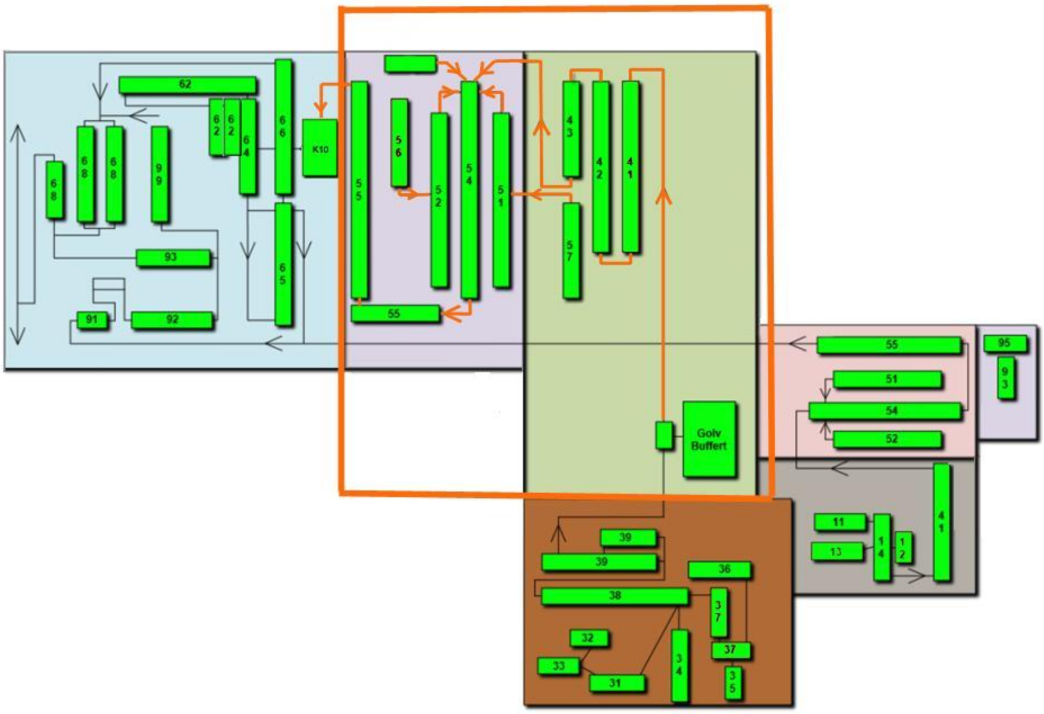

Figure 2, view over VCT's body shop. The projects geographical area is marked.

The introduction of the S60 model in the body shop at 2011 is one of many reconstructions of the body shop over the years. Continuing reconstructions due to new or renewed car models have deteriorated the system losses and rendered previous researches unusable. Therefore, this thesis is needed in order to analyse the comprehensive system losses in today's car body production.

1.2 Aim

The thesis aims at investigating the different causes of the low capacity and high variability in the production output in a limited part of the body shop. Today the capacity is somewhat sufficient but night shifts and production during weekends sometimes need to be performed when the products cannot be delivered from the body shop. The thesis will therefore study the system losses as a step towards a more efficient production. When the thesis have found the constraints in the system improving them should lead to a higher maximum capacity in VCT's body shop and thereby a more flexible manufacturing without the need for extra shifts to manage the daily demand. Knowledge about production constraints is crucial when developing production systems, hence the thesis is an important first step towards a more efficient production.

1.3 Problem formulation

Below the two main research questions are stated. The first question (RQ1) aims at locating the system constraint and the second (RQ2) evaluates how the constraints affect the throughput in the area described in figure 2 above.

RQ1 Which factors contribute to the system losses in the body shop?

RQ2 How much do the contributing factors affect the throughput in the delimited area of the body shop?

1.4 Delimitations

The time frame of the project in combination with wishes from VCT has resulted in the following limitations for the thesis:

- Geographical limitations range from the under body buffer to the K10 buffer as illustrated in figure 2.
- The thesis will not include an evaluation of suitable simulation softwares, but use the software Plant Simulation. Plant Simulation will be used since it is a recognized discrete event simulation tool that is in compliance with VCT.
- Change management and implementation of possible arisen improvements to the production flow are also not included in this thesis.
- Cost analyses of suggested improvements will not be included within the thesis.

2. THEORY

This chapter presents the theoretical background of the thesis and describes the different theories that were used in order to execute a successful project. Popular philosophies such as Lean production, section 2.1 *Lean production,* and Theory of constraints, section 2.4 *Theory of constraints,* have been considered. Furthermore Conceptual modelling and process mapping section 2.2 *Conceptual modelling and process mapping*, including Value Stream Mapping, section 2.2.1 *Value Stream Mapping*, data collection, section 2.3 *Data collection*, different bottleneck detection methods section 2.4.1 *Bottleneck detection methods* and theories regarding computerized simulation, section 2.5 *Simulation,* have been studied.

2.1 Lean production

In the 1990s Toyota caught the world's attention with their successful engineering and manufacturing of cars. They managed to design cars faster, more reliable, with a high quality and still at a competitive cost. Liker (2004) studied Toyota for 20 years and found 14 principles that together constitute the Toyota Way. The philosophy is called Lean production, originally Toyota Production System (TPS), and has a very high customer focus. Lean strives to eliminate non-value adding processes ("muda" in Japanese). The core of Lean production is to lower or eliminate waste, which is every activity that does not add value to the product or service from the customers' perspective.

Lean manufacturing is characterized by an effective organization of the manufacturing system. With faster throughput time for work in progress (WIP), smaller batch sizes, shorter set-up and change-over times, greater up time, greater schedule stability and lower rework and rectification costs. However, Lean is only directly applicable to very few manufacturers, most organizations have to adapt the tools and philosophies to fit theirs circumstances (Jina et al., 1997).

The pyramid in figure 3 below shows the four groupings of the Toyota Way's 14 principles; Philosophy, Process, People/Partners and Problem Solving. Principle 1 starts at the bottom as a foundation, which is the Philosophy and Long-term thinking. The second group addresses the Process and eliminating waste with the guidelines "The Right Process Will Produce the Right Results". The third section adds value to the organization by developing People and Partners, and the fourth section focuses on Problem Solving (Liker, 2004).

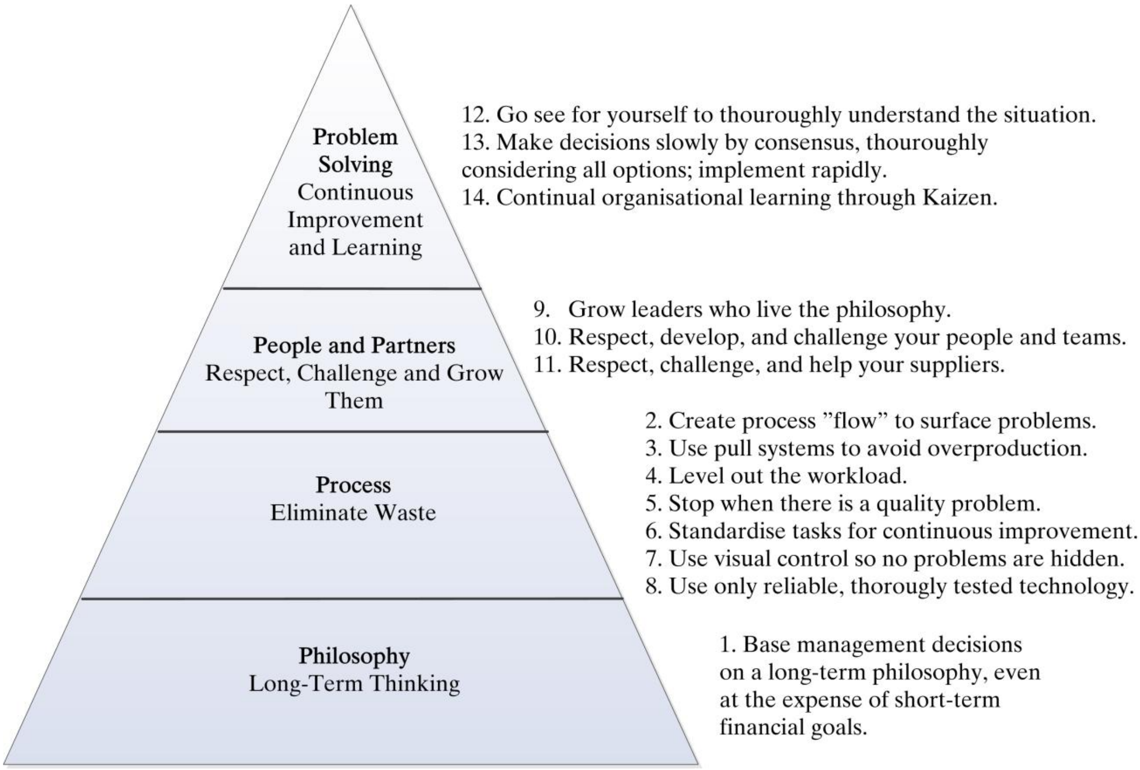

Figure 3, the 14 principles of the Toyota Way (Liker 2004).

The process related principles are of extra interest, due to the nature of this thesis. The thesis does not aim to influence the company's philosophy or to develop the people within the organization, but to investigate the system losses in the production process and look at factors that contribute to the problem. From a Lean perspective any process could be improved by using principle 2 to 8: bring problems to the surface by creating a continuous flow, use "pull" systems, level out the workload, stop for quality problems, standardize tasks, use visual control and only reliable technology. The mentioned principles are all theories for improvement that are worthy of consideration.

According to Liker's 12th principle, first-hand information is critical to ensure understanding of the system. It is of great importance to take nothing for granted, and know that data aren't facts, but only contribute to the facts. The facts remain in the process, whilst the data are one step away from the process (Liker, 2004). This is not far from the popular philosophy of learning by doing. Deep knowledge of the system can only be gained from the system itself, not from data (Liker, 2004).

Another relevant principle is the 2nd principle which emphasises the need to create a continuous flow in the production. Flow does not only increase the speed in the production, it interconnects people and processes to each other and helps surfacing problems (Liker, 2004). Levelled production with increased flow has not only been proven beneficial in mass production, but also in low-volume production. The benefit is however the same in all systems; the capacity of existing equipment can be increased without expensive investments (Djassemi and Olsen, 2010).

2.2 Conceptual modelling and process mapping

Process mapping aims at identifying, developing and improving the whole production flow and not only single processes. It is an efficient way to reduce operational waste and raise business performance (Dickens, 2007). The mapping is a key initial step to understanding the current process, Robinson et.al (2010) even states that the process mapping is probably the most important aspect of a simulation project since the developed model have impact on data requirements and the validity of the results from the simulation.

When developing the process map, or a conceptual model, it's important to find the right level of detail for the project, simplifications of the reality are often needed in order to ease the mapping process and make the model easier to understand (Robinson et al., 2010). However, the level of detail depends entirely on the aim of the project. Banks (1998) suggest that the conceptual model should be developed by focusing on the projects key research questions abstracted from the objectives in order to find the right level of detail. To further narrow down the model the output measures necessary to answer the research questions should be defined (Banks, 1998).

When the process itself have been identified it is important to define the process owner. The process owner is the one responsible for decisions regarding the process, and should be considered the client for any improvement project performed (Conger, 2011). Therefore, Conger (2011) emphasizes that interviews with affected parties should be held before the process mapping begins. Customers, suppliers and operators in the process have different views of the process which should be taken into consideration. Dickens (2007) have a similar view on process mapping, which states that a team of key internal stakeholders should be put together in order to gather the all their great knowledge, define the problem and come up with possible solutions.

Robinson (2010) states that the outcomes of a process map are a rather vague concept that could result in various different models. An example of this is Robinson's (2010) figure, illustrated in figure 4, where the conceptual models area is defined within the ellipse. According to the figure the conceptual model could be an outcome from all processes, like an improved understanding of the real world or a computer model. However, the models are often illustrated in either flow charts or in tabular form (Linton, 2007). Figure 4 also illustrates that the conceptual model is dependent on and consist of four main elements; the objectives of the project, the output of the project that answers the research questions, the projects inputs and the models scope and level of detail. Robinson (2010) further states that the design of a conceptual model is an iterative process that continually needs to be revised through the project.

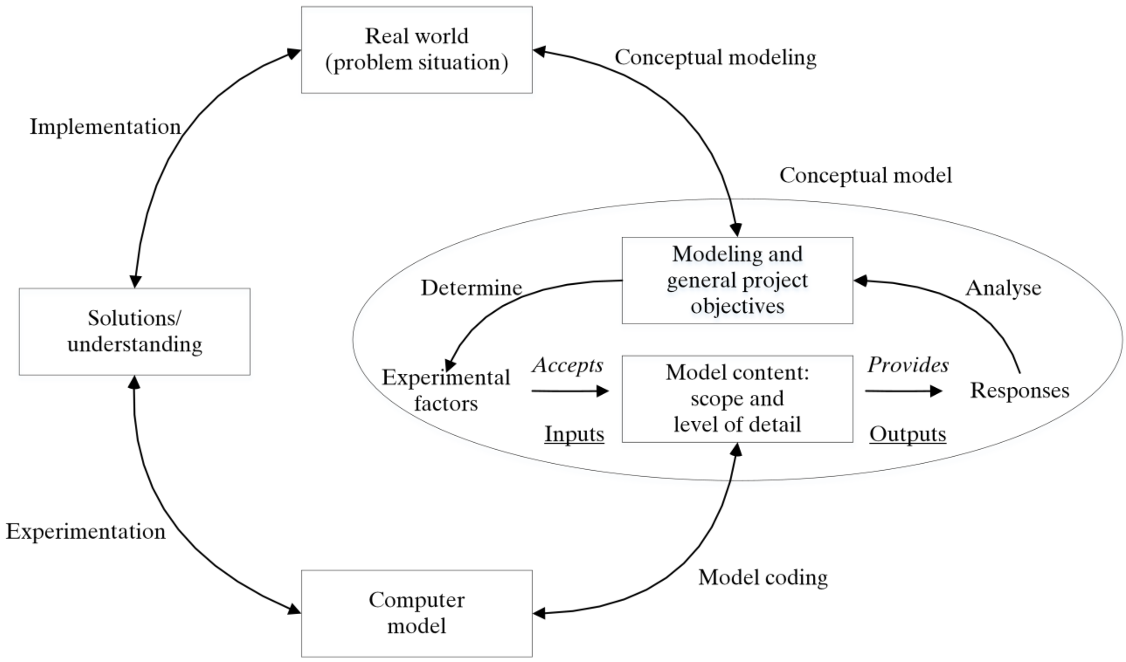

Figure 4, Illustration of conceptual model elements (Robinson, 2010).

Damelio (1996) speaks of three main tools to visualise work: relationship maps, cross-functional process maps and flowcharts. The first tool, relationship maps, shows the interrelations between the suppliers, the organization and the customer. These three components have to be identified. “The organization” could be the entire company, a factory or even a single department and the suppliers and customers would then be defined based on that first selection (Damelio, 1996).

The second tool is cross-functional process mapping, which illustrates workflows following their distinct path as they use activities to transform resources into outputs. The process touches several functions or departments in an organization; hence it is a “cross-functional” process. A swim lane diagram is one type of cross-functional map that illustrates the different functions as horizontal bands, the workflow as interrelated activities and supplier-customer relationships when a work item crosses over into another function, or swim lane (Damelio, 2011). A swim lane diagram should have one start symbol and one end symbol, in rare cases a process can have two start symbols, however then it is most likely that the process is in fact two processes (Conger, 2011).

The third tool is flow charting, which is used to graphically visualize the sequence of work activities that makes up a process. Flowcharts focus on what actually happens and helps to make types of waste in a non-value-adding activity visible. Intelligence can be included into the chart by using the appropriate symbol for the right action (Damelio, 2011). One of the most used and recognized tools for flow charting is Toyota Production Systems’ standard Value Stream Mapping, which is further described below.

2.2.1 Value stream mapping

Value Stream Mapping (VSM) is a flowcharting method that originates from Toyota’s Lean production philosophy. It aims to give a better understanding of the system as well as showing where improvements can be made by reducing or removing wastes. A VSM visually expresses the current production process as a simplified snapshot of the system, showing all steps of the process, both value-adding and non-value-adding. The icons used in the VSM are standardized and some of them are presented in figure 5 below.

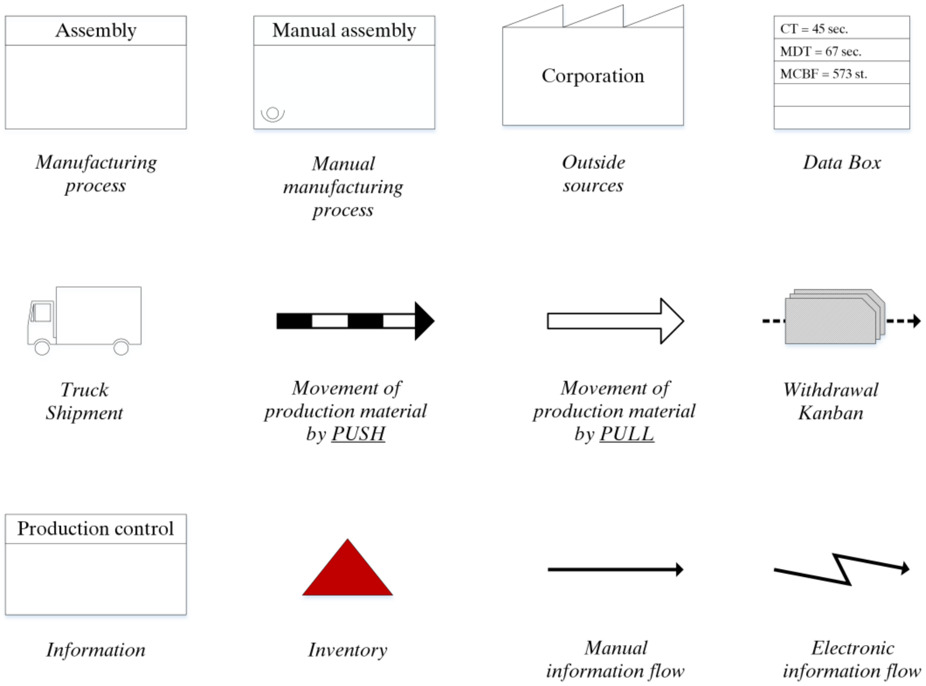

Figure 5, example of VSM icons (Rother & Shook, 2003).

VSM is manufacturing oriented, though similar approaches exist in other application areas. By creating a VSM it is possible to visualize the entire manufacturing and information flow and see how operations currently communicate with production control and each other (Tapping et al., 2002). All actions needed to create a product or service and bring it to a customer, in-house or external, are visible in the map. It helps focusing on improving the whole system and not only optimizing specific parts (Rother & Shook, 2003).

Tapping et al. (2002) emphasizes the importance of going to the factory floor in person, rather than relying on past reports and already collected data. To stress the accuracy of the data is completely in line with Toyota Way's 12th principle, mentioned under section 2.1 *Lean production,* that stands for "Go see for yourself to thoroughly understand the situation" (Liker, 2004). Liker (2004) means that this is of highest importance since no problem solving can be made without fully understanding and deeply analysing the current situation.

The creation of a value stream map

According to Rother and Shook (2003) the VSM approach follows four main steps:

1. Select one product family as the target for improvement.
2. Construct a current state map for the product value stream, using information gathered from the actual production process.
3. Map the future state.
4. Create a plan for the realisation of the future state.

One could say that the four steps represent Plenerth's (2007) four phases: Preparation, Current state map, Future state map and an Improvement plan. The first two steps aims at deciding the scope of the mapping and gaining knowledge of the system, whilst step 3 and 4 look into the future and tries to create an improved future state. Therefore, only the first two steps are of highest importance to the thesis, since the thesis does not aim at offering a solution to identified problems. Hence a VSM would serve as a conceptual model of the production system, not as a solution or plan for a future state.

When level of detail and product family have been chosen the drawing of the current state map can start. Tapping et al. (2002) recommends the following approach when drawing the map:

1. Start with drawing rough sketches of the main production operations.
2. Chose 7 to 10 key attributes to focus on when collecting data. Go to the floor and start at the most downstream operation. Work upstream through the chosen flow, collecting the process data.
3. Discuss and analyse the gathered data. Check so that all necessary data are collected.
4. Repeat step two if necessary.

When these steps have been finished the actual drawing of the map can start. Starting with the supplier to the left and finishing with the customer to the right. The manufacturing operations are drawn at the bottom of the map; indicating each process by a process icon. The process attributes are added in data boxes below the process icons. Thereafter all inventories are illustrated in the flow by triangular icons with work in progress quantities. The material- and information flow are added in the map as well as pull and push arrows. Lastly, a timeline is drawn under the processes in order to show the production lead-time (Rother and Shook, 2003 and Tapping et al., 2002). An example of a VSM is illustrated below in figure 6.

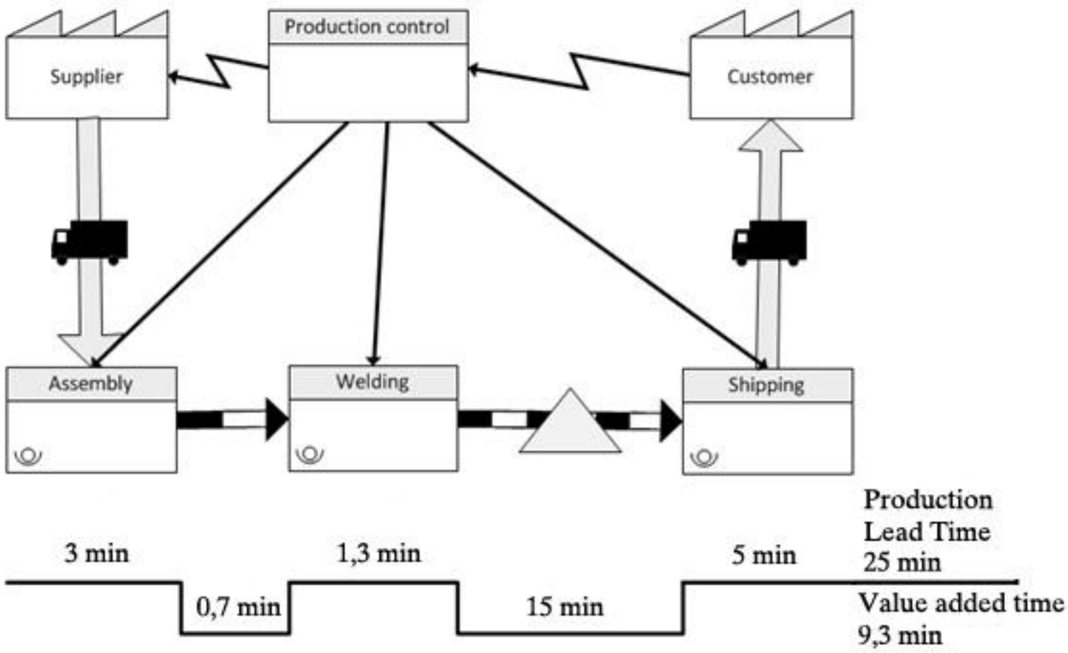

Figure 6, example of Value Stream Map.

2.3 Data collection

A wide range of data is needed to perform process mapping and flow simulations, it stretches from production orders and production batches to machine failure frequencies and repair times. The resulting process map and flow simulation are highly dependent on the quality of the data, which makes data collection a timely but very important task (Banks, 1998). According to Skoogh and Johansson (2008) the data collection often represents one third of the project's total time. The first step when collecting data is to identify the parameters that are of importance for the study. Depending on the system complexity and the nature of the task an appropriate level of detail need to be selected. To gather the right parameters at the right level of detail is of high importance due to the time consumption (Skoogh and Johansson, 2008).

The required data could be collected in many different ways. In order to ease the collection of the needed data Robinson and Bhatia (1995) recommend to categorize the data in three different categories, this approach is also much alike Banks' (1998) model for data collection. Category A handle all available data, category B handle the data that not are available but collectible and the third, category C, handle the data that not are available neither collectible.

The available data for Category A could be collected through the company's databases such as Corporate Business Systems or through previous studies. All this data need to be questioned; what is the source, what is collected, when was it collected and how was it collected? Do the data fit the scope of the project? Is the level of detail relevant? (Banks, 1998). The data have to be investigated, defined and validated so that it thoroughly fits the project. Category B data need to be collected by hand, for example by timing the process and preferably while the processes mapping is performed. The data in category C are not accessible and therefore only based on estimates and approximations. In order to collect these data discussions with experts within the relevant area could be done, historical data from similar processes and systems could be investigated or customer could be asked for an educated guess in order to get an approximation of the values (Robinson and Bhatia, 1995).

Banks (1998) suggests that the data available should be used in the beginning and that more data should be request when needed. With this approach data collection and model conceptualization can be performed in parallel. Assumptions should be made when necessary. The project shouldn't come to a halt due to missing information, when an assumption can lead the project forward. Afterwards the sensitivity of the model should be evaluated to see whether it is sensitive to the assumption or not, though re-evaluations of assumptions has to be encouraged since knowledge of the system is gathered continually. All assumptions have to be validated before presenting the results (Banks, 1998).

While collecting data it is of great importance to use a system for the storage of data so that it is easily accessible and understandable. Data should be stored at one place, a spread sheet could be used for smaller projects but for bigger projects it is more preferable with a database. The collected data also need to be thoroughly investigated and validated in order to make the analysis of the process mapping and simulation model as smooth and accurate as possible (Robinson and Bhatia, 1995).

2.4 Theory of constraints

Theory of Constraints, TOC, is a management philosophy developed by Eliyahu Goldratt. TOC gradually emerged from Goldratt's theory Optimized Production Timetables, OPT, which is described in his best-selling book *The Goal* from 1984. The OPT theory is, according to Rahman (1998), based on nine rules; these are summarized in the following statements. It is highly important to balance the flow, and not the capacity. The utilisation and activation of a resource is interchangeable. One hour of lost production at a bottleneck is one hour lost for the total system and all different constraints should be considered before establishing schedules.

The essence of the TOC philosophy is the fact that all systems have constraints, for example a bottleneck, which influences the entire system's performance. The existence of a constraint gives the possibility of improvements and since a system always will consist of at least one constraint TOC is a continuous process. The continuous improvement is the last aspect out of five focusing steps in the TOC approach to reduce or remove constraints; these are according to Goldratt and Cox (2004) as follows:

1. Identify the system's constraint(s).
2. Decide how to exploit the system's constraint(s).
3. Subordinate everything else to the above decision.
4. Elevate the system's constraint(s).
5. If in the previous steps a constraint has been broken, go back to step 1, but do not allow inertia to cause a system's constraint.

The TOC method's application on logistical systems should be controlled by the drum-buffer-rope, DBR, methodology and managed by time buffers, according to Rahman (1998). The methodology of DBR was presented by Goldratt and Cox in *The Goal's* sequel *The Race* 1986. The DBR methodology coordinates material utilisation with the systems resources and reduces the systems complexity by focusing on critical resources. This is done by firstly the drum, the pace of the constraint, which sets the pace for all stations in the system. Strategically placed buffers makes sure that the constraint never lack of material and prevents variations in the systems output. Finally the rope handles the communication and make sure that the products are pulled in to the constraint at the right pace (Gardiner et al, 1993) and (Rahman, 1998).

Time buffers prevent disruptions at non-constraint resources and could be divided into three different categories; constraint buffers, assembly buffers and shipping buffers. Constraint buffers are placed in front of bottlenecks in order to make sure that the constraint can follow the schedule. Assembly buffers contains products that later will be merged with products from the bottleneck. Shipping buffers ensure that the delivery dates are held (Rahman, 1998).

Below, the first step of TOC's philosophy, *identify the system's constraint(s),* is studied further by describing different methods to identify bottlenecks in a system.

2.4.1 Bottleneck detection methods

The classification of a bottleneck may vary. Normally the definitions include but are not necessarily restricted to: physical constraints, economical characteristics, output limitations, capacity utilisation, work-in-process limitations and capacity in relation to demand (Lawrence and Buss, 1995). Within this thesis a bottleneck is simply defined as the production system stage that has the largest influence on limiting the throughput in the system.

All manufacturing systems have constraints, which control their performances. Hence to improve performance it is important to find and elevate the constraints, as mentioned earlier under section *2.4 Theory of Constraints*. There are several methods used to find constraints, or bottlenecks, and their success rate vary depending on the type of system. Constraints are not easily identified using conventional methods (Lima et al., 2008). Since manufacturing systems are dynamic, their state can vary with seasons and even during a single workday, therefore the constraint can move i.e. be time dependent (Roser et al., 2003). In literature there are many different methods for bottleneck detection. The three main methods could be identified as the utilisation method, waiting time method and shifting bottleneck method, all of which are described further below.

Utilisation method

When using the utilisation method for bottleneck detection, the machine with the largest active time in percentages is defined as the bottleneck. The active time includes more than just machining time, since for instance breakdown times also have influence on the utilisation. With this method a primary bottleneck can be identified, but no secondary or non-bottlenecks can be detected (Roser et al., 2003). Another limitation is that the method is only suited for steady state systems and with its need for data from a long time period it can only determine average bottlenecks and not momentary ones (Roser et al., 2002). On the other hand, with a long time perspective in mind an average bottleneck is found quickly using the utilisation method (Lawrence and Buss, 1995).

Waiting time method

The waiting time method defines the bottleneck as the machine where parts have to wait the longest, either by measuring the queue length or longest waiting time. This method can find both momentary and average bottlenecks, by comparing the queue lengths or the waiting times (Roser et al., 2002). However, the method is limited to usage in systems where the buffers have unlimited capacity, also the supply must be smaller than the system capacity in order to not fill the queues permanently, rendering the analysis impossible (Roser et al., 2003).

The shifting bottleneck method

The shifting bottleneck method defines the machine with the longest uninterrupted active period as the bottleneck. The method can detect both momentary bottlenecks and average bottlenecks, depending on the chosen timeframe. Furthermore it does not only detect primary bottlenecks, but also secondary and non-bottlenecks, making it possible to improve system throughput using a two-pronged approach by both focusing on reducing the cycle times of the primary bottleneck, and also ensuring a steady supply to the primary bottleneck by improving the secondary bottlenecks (Roser et al., 2002).

The shifting bottleneck method determines whether a machine at any given time is a sole bottleneck, a shifting bottleneck or a non-bottleneck. To turn this momentary approach into a search for an average bottleneck during a time period, the percentage of time when a machine is a sole bottleneck and a shifting bottleneck is measured. The bottleneck detection method that uses utilisation and the one that uses waiting time do not take time variations into consideration, but the shifting bottleneck method does (Roser et al., 2002).

Comparison of bottleneck detection methods

Roser et al. (2003) made a comparison between the three bottleneck detection methods and applied it on a system containing AGVs (Automatic Guided Vehicles). A brief review of their results is given below.

The utilisation method searches for the most active machine and defines it as the bottleneck. The method lacks ability to say which machines are secondary bottlenecks and the analysis is often not dynamic enough. The waiting time method looks for the machine for which the parts have to wait the longest, defining that machine as the bottleneck. In order to use the waiting time method buffers should have infinite capacity and the system capacity should be larger than the supply, otherwise the queues will be permanently full. The limitations of the waiting time method are large, since the method cannot account for the AGVs themselves even though they are a kind of queue (Roser et al., 2003).

Moving on, the shifting bottleneck method determines the bottlenecks by usage of the active times, similarly as the utilisation method does. Note that active time includes more than just machining, for example AGV transportation and breakdowns. The difference is however, that the shifting bottleneck method does not use percentages of active time, but instead the uninterrupted duration that a machine is active. This approach can find the system constraint at any given time, by identifying the machine with the longest active period. Furthermore Roser et al. (2003) concludes that even though interconnected stations have the same utilisation degree they could prove to constrain the system unequally using the shifting bottleneck method. In a series of interconnected stations the stations in the beginning are more often the bottleneck than later stations, and the risk of starving later stations increases with the number of stations in the series (Roser et al., 2003).

Furthermore the method distinguishes between shifting bottlenecks and sole bottlenecks, the difference being whether or not the bottleneck serves as a constraint by itself or if it overlaps with other bottlenecks. This distinction is of outmost importance when it comes to a bottleneck probability analysis (Roser et al., 2003). It is also notable that the shifting bottleneck method shows a much clearer distinction between the more probable and less probable bottlenecks (Lima et al., 2008).

Selection of bottleneck detection method

Lima et al. (2008) proposes a methodology for selection of the best suitable bottleneck detection method. The selection should be based on the degree of fluctuations in the system, which can be objectively decided using the following equation:

$$elf = \frac{\sum station}{\sum_n^1 frequency}$$

Where *elf* is the fluctuation factor, which indicates a high fluctuation if below 0.5 and a low fluctuation if larger than 0.5. The numerator "station" is the total number of production stations involved and denominator "frequency" describes the "Sole Bottleneck Frequency" per station, which is easily determined using a simulation. With the fluctuation factor set table 1 could be consulted for recommended methods.

Method **Situation**	Utilization factor	Queue size in front of machine	Waiting time in front of machine	Active time period	Shifting bottleneck method
Low mix Low station no. Low fluctuation	Recommended	Recommended, but queue size should be infinite	Recommended, but queue size should be infinite	Recommended	Recommended if other methods are not applicable
High mix Low station no. Low fluctuation	Recommended	Recommended, but queue size should be infinite	Recommended, but queue size should be infinite	Recommended	Recommended if other methods are not applicable
Low mix Low station no. High fluctuation	Low recommended	Low recommended (especially if queues are not infinite)	Low recommended (especially if queues are not infinite)	Low recommended	Recommended
High mix High station no. High fluctuation	Low recommended	Non recommended	Non recommended	Low recommended	Recommended

Table 1, recommended bottleneck detection method based on situation (Lima et al. 2008).

2.5 Simulation

Simulation is a powerful tool for both existing and future systems. It makes impossible analyses possible and works excellent as a tool for decision-making. Furthermore it is a money saver, since it is much more costly to experiment with a real production system rather than with a simulation (Shannon, 1998). Banks (1998) defines simulation as an imitation of a real-world process over time, which is used to analyse the behaviour of a system, ask what-if questions about the real system and aid in the design of real systems. Shannon (1998) defines simulation as the process of conducting experiments with a model of a real system, with the purpose of gaining knowledge of the system and /or evaluating strategies for the operation of the system.

John S. Carson II (2005) has created a list of situations when simulation is most useful. The points which fit the thesis have been rewritten and are presented below:

- There is no simple static model or calculation accurate enough to analyse the situation.

- The real system is regular and interactions can be defined.

- The real system has a level of complexity that is difficult to grasp in its entirety. It is difficult or impossible to predict the effect of proposed changes.

- A tool that can get all members of a team into more common understanding is needed.

- Simulation is an excellent educational device. In some cases the simulation animation could be the only way to visualize how parts of the system influence each other and contribute to the overall system.

Banks (2005) states many advantages with simulation, they include but are not limited to the aspect of independent testing of changes (without disturbing the production), the opportunity to compress and expand time and creating a better understanding of an otherwise to complex system.

There are of course also disadvantages with simulation. For example; special training is required to build and interpret a simulation model, simulation could be used inefficiently when there are easier solutions and simulation modelling could be costly (Banks, 2005).

2.5.1 Types of simulation

When determining the type of simulation model needed the nature of the real system decides which approach to choose. The two central approaches are discrete event simulation and continuous simulation. In most simulations time is an important variable, to which other variables are dependent. In a discrete event model the dependent variables change at specific points in time, called event times. In continuous modelling, the dependent variables are continuous functions of time (Banks, 1998).

Most discrete-event models include a statistical distribution; hence they are stochastic and have random variations (Carson, 2005). A model could also be deterministic, which means that is has no random variations and therefore always produces the same output given the same input (Banks, 2010). The text will from here on focus on discrete event models with stochastic variations, since this approach is most applicable on the production system being modelled.

2.5.2 Discrete event simulation

Discrete event simulation (DES) models depend on time, that is, they are dynamic (Banks, 2005). DES models are based on the concepts of state, events, activities and processes. The states change instantaneously, but only at discrete times called event times. An event can trigger new events, activities and processes. All events can be categorized as primary or secondary events, where primary events are triggered by data, whilst secondary events occur automatically due to model logic (Carson II, 2005).

An efficient model has sufficient complexity to answer stated questions, but is at the same time not too complex. Since a model imitates a real system, the boundaries must be set with caution (Banks, 1998). All relevant system components must be described in the simulation model, but their level of detail can vary with their relevance for the study.

2.5.3 The steps in a simulation study

Banks (1998) provide a model builder guide for a well-performed simulation study, this guide is visualized in figure 7 and each step is further described below.

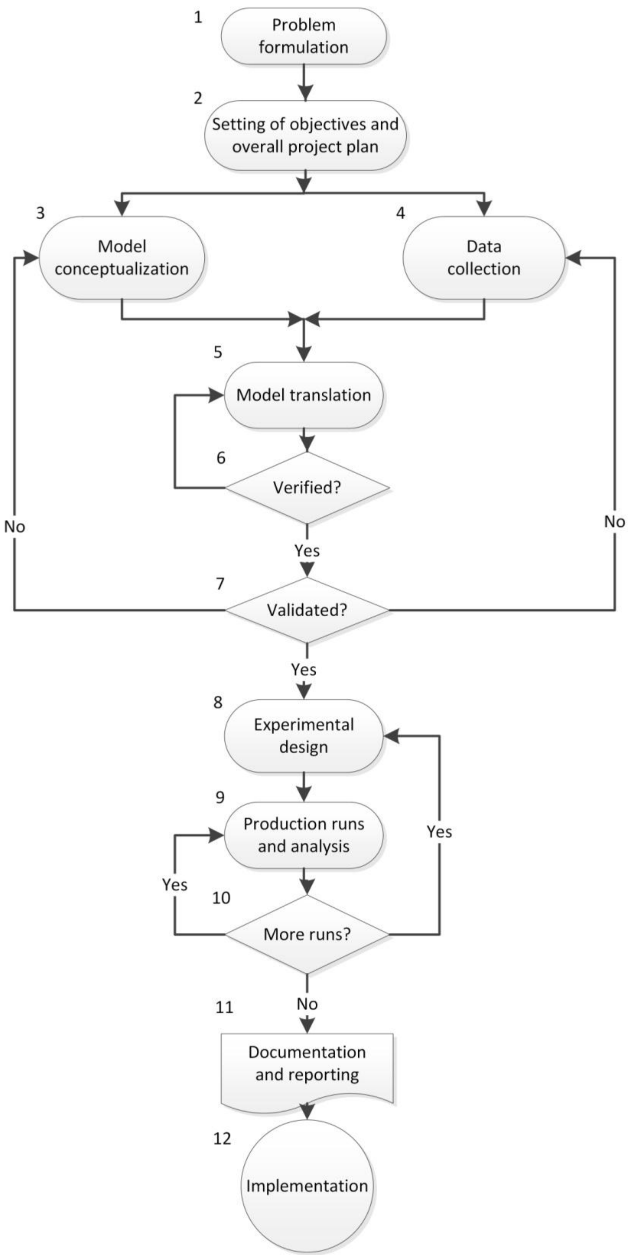

Figure 7, steps in a simulation study (Banks, 1998).

1. Problem formulation
The simulation modeller and the client which is the owner of the problem need to make sure that they have a common understanding of the problem. Either the client can formulate the problem, which the simulation modeller has to fully understand, or the simulation modeller can prepare a problem statement, which then has to be agreed upon by the client (Banks, 1998).

2. Setting of objectives and overall project plan
The objectives should stand in relation to the questions stated in the problem formulation. The overall project plan specifies resources needed in terms of for example time, personnel hardware and software. The plan could also include the different steps in the project, the output at each stage as well as the cost of the study (Banks, 1998).

3. Model conceptualization
As a starting point a simplified model should be created, which can gradually grow into a more appropriate complexity to be able to answer the questions of the study. The involvement of the client should continue throughout the building. This will enhance both the quality as well as the client's confidence in the model (Banks, 1998).

4. Data collection
A wide range of data is needed to perform flow simulations, it often stretches from production orders and production batches to machine failure frequencies and repair times. Depending on the system complexity and the nature of the task an appropriate level of detail need to be selected,. The resulting simulation is highly dependent on the quality of the data, which makes data collection a timely but very important task (Skoogh and Johansson, 2008) and (Banks, 1998). The data collection need to be thorough, and the source as well as the purpose of the collected data need to be questioned in order to prove its usefulness. This topic is further discussed in chapter *2.3 Data collection.*

5. Model translation
This step consists of the translation of the conceptual model from step 3, the conceptual model, into a computer-recognizable form with the input from the data collection (Banks, 1998).

6. Verified?
The computerized model is verified in order to ensure that the model behaves in accordance to the conceptual model and that the code is correctly written. The verification of the model should be carried out before the validation of the model and continuously throughout the modelling. This since the code has to be correct and in accordance to the conceptual model before actions is performed to ensure that the model reflects the reality at a satisfying level. However, these actions are based on that the conceptual model is thoroughly validated to fit the reality of the system (Sargent, 1984) and (Banks, 1998).

7. Validated?
When the model has been verified and works as it is intended to do due to the conceptual model it is time to make sure that it is a representation of the real system. The validation process consists of several different phases of the modelling process and could according to Sargent (1984) be described by the help of figure 8 below.

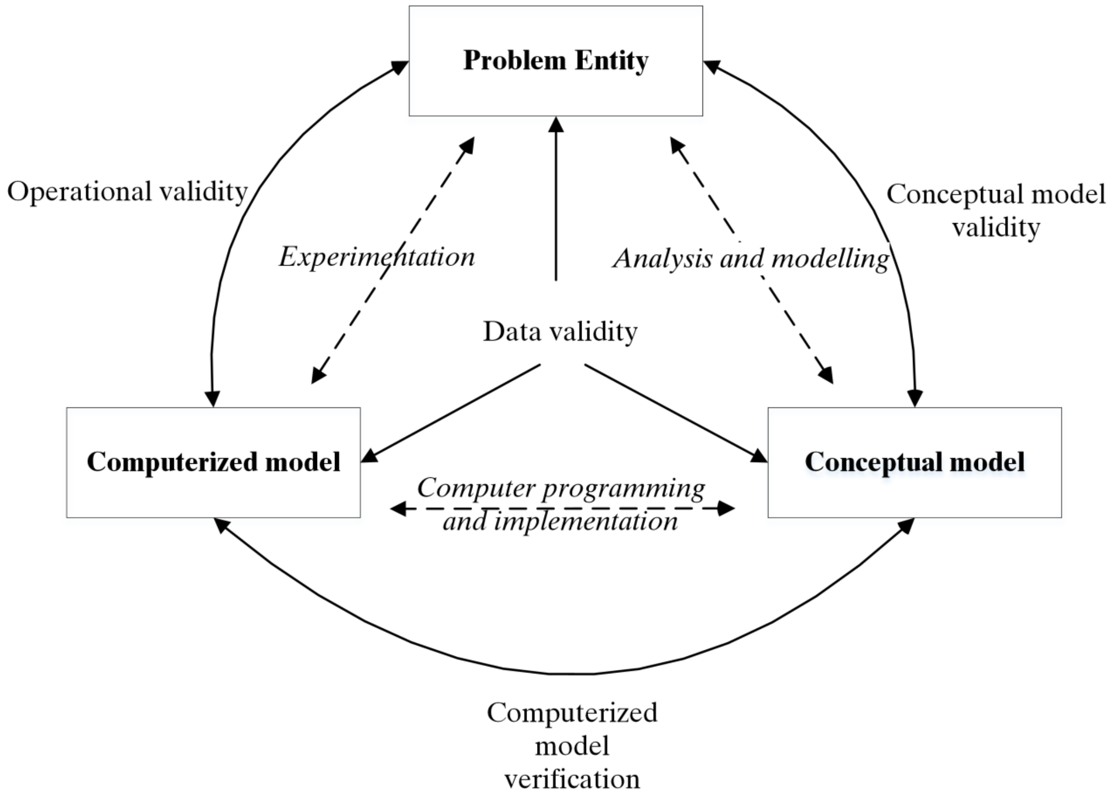

Figure 8, the process of a simulation model validation (Sargent, 1984).

The *Problem Entity* represent the real system or the system to be investigated, the *Conceptual Model* is developed for the particular study and is the logical representation of the problem entity and the *Computerized Model* is the conceptual model transferred to a computer program. These three stages of the modelling are connected to each other by three different phases. The conceptual model is constructed in an analysis and modelling phase and the computerized model in a computer programming and implementation phase. Finally results and conclusions are constructed by performing different experiments on the computerized model and compare that to the problem entity in the experimental phase.

Verification and validations should continuously be performed on the above simplified steps of a simulation model. The validity of the conceptual model should be confirmed by tests on the theory and assumptions that the conceptual model are built upon. The conceptual models logic should also represent the problem entity on a satisfying level. The computerized model should be verified in order to represent the conceptual model, as described under the previous section *6. Verified?* Operational validity is performed in order to ensure that the computerized model is a good representation of the reality. This could preferably be performed by experimentally compare the system and the models output for different conditions. However, a perfect replica of the real system is not necessarily the best to aim at when validating the computerized model. This since that it may be too time consuming or too costly to perform all different experiments to test all different conditions for the model. Also, all different conditions may not be relevant to test for the problem entity. Further validation should be performed by asking knowledgeable people if the computerized model seems to fit its purpose and if it is a good representation of the real system. Finally, when building the model it is of highly importance that the data used in the model is validated and correct (Sargent, 1984) and (Bank, 1998).

8. Experimental design

When deciding upon which experiments to run, it is important to define required length of the simulation runs, and the number of runs for each experiment (Banks, 1998).

9. Production runs and analysis

In order to estimate performance measures for the experiments, the simulation model is run and analysed (Banks, 1998). Data recordings from the warm-up phase of the simulation run can be disregarded since the system has not yet reached its steady state. During the warm-up phase the model might not behave in accordance with the real production, since the model is empty in the beginning (Grassmann, 2008).

10. More runs?

When step 9 is performed and analysed the modeller can determine whether more runs or additional scenarios need to be performed (Banks, 1998).

11. Documentation and reporting

Documentation needs to be carried out throughout the simulation project. To assure that the right decisions were made and that they were well-founded it is important to know which alternatives where considered and why.

12. Implementation

If the experiments are successful and the client is satisfied with the execution of the project there is a chance that the results of the study will be implemented in the real system (Banks, 1998).

2.5.4 The software: plant simulation

The simulation modelling has been carried out using the Siemens software Plant Simulation, which is a Discrete Event Simulation software with focus on logistics systems for example in a production. Plant Simulation is designed for modelling and simulation of systems, to enable optimization of material flow, use of resources and logistics for global production facilities as well as specific production lines. The software comes with advanced analysis tools such as bottleneck analysis, statistics and graphs which help in the evaluation of different scenarios in a present or future system (Siemens Industry Software AB, 2013).

3. METHODOLOGY

This chapter describes the methods that are used throughout the thesis. The general framework for the execution of the thesis is visualised in figure 10 below. Each step in the figure is further described under respective section below.

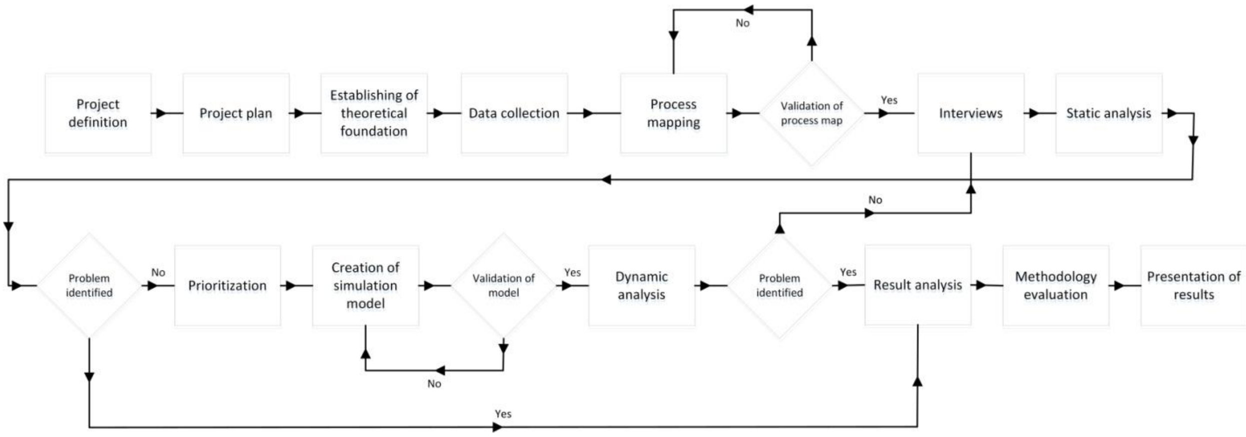

Figure 9, methodology map.

As described by figure 10 the thesis starts by defining the project and creating a project plan, see section *3.1 Problem definition and Project plan.* Thereafter a theoretical foundation is established and a process mapping is performed in order to gather necessary knowledge of the execution of the thesis and to thoroughly understand the production system analysed. These steps are included in sections *3.2 Establishing of theoretical foundation* and section *3.3 Conceptual Modelling and Process Mapping.* Parallel with the process mapping and continuously through the thesis data are collected, this process is described in section *3.4 Data collection.*

When the process is mapped and validated interviews are performed with knowledgeable people in order to further validate the process mapping and to collect information so that a comprehensive static analysis can be performed. This is described in section *3.5 Interviews* and *3.6 Static analysis*. If no results are extracted from the static analysis the problem is further scrutinized in a dynamic analysis by creating a simulation model. Since the studied area is a rather large geographical area it is desirable that a prioritization first is performed so that the creation of the simulation model could be simplified. These steps are described in section *3.7 Prioritization of problem areas* and *3.8 Simulation.* If the dynamic analysis results in an identified problem the methodology needs to be evaluated and questioned and finally the results can be presented, further described in section *3.9 Methodology evaluation* and *3.10 Presentation of results*.

3.1 Project definition and project plan

A problem definition is set in cooperation with tutors at Volvo Cars Torslanda (VCT) and Chalmers University of Technology. A number of research questions are formulated in order to keep the focus of the project. When the problem definition is finished a project planning report, including a project plan, will be written and approved by VCT as well as Chalmers University of Technology before the project can start.

3.2 Establishing of theoretical foundation

Relevant theories and methods are examined in preparation for the study of the capacity problem. The literature research handles the subjects of data collection, process- and value stream mapping, bottleneck detection methods and discrete event simulation. Basic knowledge about production systems is already gathered from courses taken at Chalmers University of Technology, such as Lean Production, Production Management and various project courses. Deeper knowledge within the subjects is gathered through researching books, scientific articles and PhD theses.

3.3 Conceptual Modelling and Process Mapping

The process mapping follows the construction of a Value Stream Map (VSM), since VSM is a standardized and well known tool. According to Tapping et al. (2002) it is preferable to start to draw ruff sketches of the production flow before starting to map the processes. Therefore, maps of the body shop are studied before a site visit in order to get a first view of the plant and provide guidance in the following process mapping. Before the site visit a number of main data parameter are constructed so a focus is set when performing the mapping. Careful preparations before the site visit are of extra importance when studying a big geographical area as in this thesis.

During the site visit the mapping is performed by walking upstream from the last station to the first station of the production flow. The product group to be included in the VSM map is pre-decided by VCT since the thesis aims at investigating a certain part of the body shop. When deciding upon level of detail aspects such as needed output for analysis and possibilities to extract data are considered.

3.4 Data collection

Large amounts of data are gathered during the project. Some data are downloadable from VCT's internal databases, but in every case the data need to be reworked in order to suit its purpose. Some data are collected manually by timing the events on the shop floor, this is especially necessary when it comes to validation of the downloaded data. The collected data are classified according to the three categories mentioned in section *2.3 Data collection*; Category A - Available, Category B - Not available but collectible and Category C - Neither available nor collectible.

The data which are collected include cycle times, transport times, buffer levels, throughput times and production disturbances. These variables all affect the system capacity and are therefore necessary for the study of system losses. The cycle times are collected for each station, with regard to the five different car models. This is important in order to contribute to the analysis of the process mapping and to see whether the stations have somewhat balanced cycle times or not. Transport times, which are wastes, are analysed in search for deviations from reasonable times. The buffer levels play a crucial role in pinpointing where the system has difficulties keeping up with the takt, and so does the throughput times. Production disturbances stand in immediate relation to the capacity and are analysed with regard to bottleneck analyses to find the severest constraint in the production system.

3.5 Interviews

Interviews are held in order to collect thoughts from relevant people and validate or get new perspective on the static analysis. In order to get fair results with a width of knowledge the interviewees are from different departments and handle different work tasks. It is also preferable if interviews are held with people on all levels of the organisation, from shop floor to managers. In order to get the interviews as equal as possible the same questionnaire are used during all interviews. It is preferable if the interviews start with wide and comprehensive questions in order to not influence the interviewee.

3.6 Static analysis

The static analysis is initially performed on a rather comprehensive level, and thereafter again on a more detailed level in accordance with the prioritisation, see section *3.7 Prioritization of problem areas* below. The analyses are performed with help of the process mapping and by the collected data. To identify problem areas, a static bottleneck detection is performed.

3.7 Prioritization of problem areas

In a complex system such as a production plant there are many different problems at any given moment. To find the most pressing problems both interviews and data are analysed, see section *3.4 Data collection* and section *3.5 Interviews* for further description of selected methods. Data are highly objective in comparison with interviews, although data collection can be biased depending on the viewer's perspective. This makes interviews a good supplement to data collection, since the aim of the data collection can be directed based on the interviews.

All points of interest, both based on interviews and static analysis are collected, considered and analysed. When selecting what to move forward with a qualitative evaluation, based on the categories that have the largest influence on the throughput of the system, are performed. Categories which do not fit within the thesis limitations are shelved.

3.8 Simulation

If the static analysis shows that further research are needed in order to locate the factors causing the body shops system losses a dynamic analysis are be performed. The dynamic analysis are performed in a simulation model and most likely in a discrete-event simulation model since they are, according to Carson (2005), stochastic and have random variations and therefore best represent VCT's production system of today.

When building a discrete-event simulation model there are, according to Banks (1998), a number of steps that should be considered, these are further discussed in section *2.5.3 The steps in a simulation study.* Since a static analysis is done before the simulation model are constructed large parts of the four first steps of the simulation model are already completed. For example problem formulation and setting of objectives and overall project plan are already executed. For the model conceptualization the VSM map constructed during the process mapping is used and a large number of data are already gathered for the static analysis that hopefully also contributes to the simulation model. However, since the simulation model highly depends on the quality of the data it is important to make sure that the data are correctly used in the simulation model and if necessary that new data are gathered.

When these steps are finished the conceptual model is translated into a simulation model. Since VCT uses the program Plant Simulation it is pre-determined that the model is built in this program. After the model is built it is time to verify that it behaves as the conceptual model and validate it to make sure that it is a representation of VCT's production system. Once a representative model is constructed experiments are designed to dynamically locate system losses and the dynamic analysis is performed.

3.9 Methodology evaluation

Once the problem is identified and the results are reached the methodology have to be examined and questioned to assure the validity and correctness of the results. Pros and cons with the methodology and strengths and/or weaknesses are preferably stated and discussed.

4. FACTORY DESCRIPTION

This chapter presents the Volvo Cars Torslanda (VCT) production plant where the thesis has been carried out. VCT is a complete car manufacturer that delivers to customers all around the world. 155 411 cars were produced here in 2012. The factory is divided into three main parts: the body shop, the paint shop and the final assembly, as illustrated in figure 9 below.

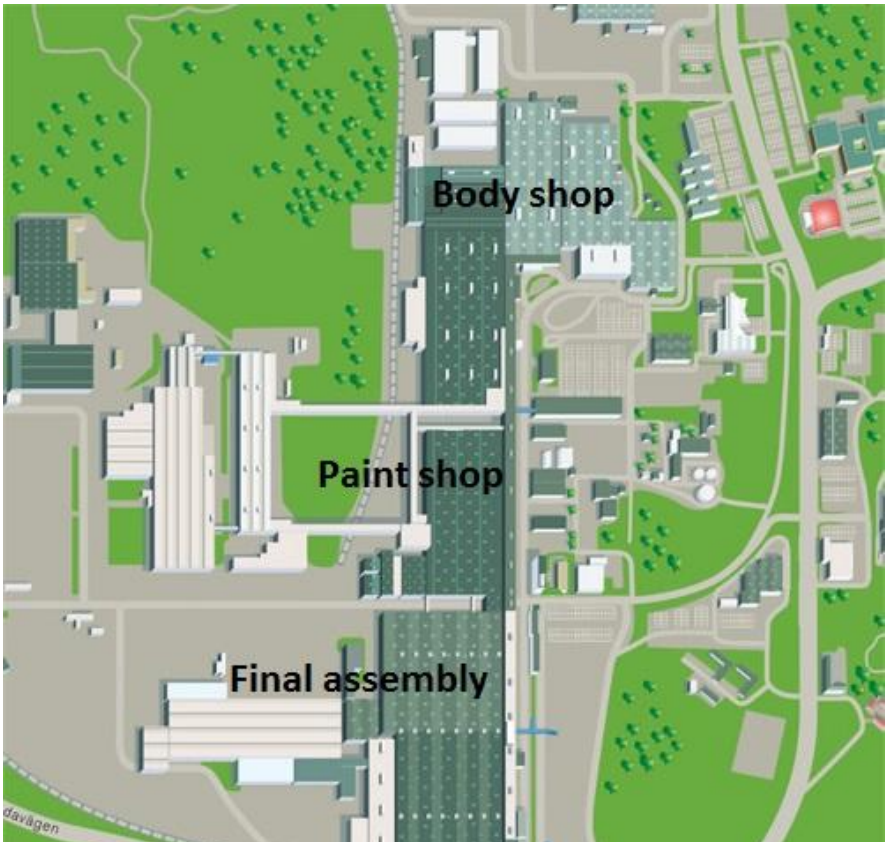

Figure 10, an overview of Volvo Cars Torslanda.

The thesis's geographical limitations, see figure 2 at page 2, are within the body shop where the complete body in white (completed car body) is welded together before it is sent to the paint shop, see section *4.1 The body shop* below for a more thorough description of the production steps in the body shop. After the paint shop the painted body is assembled into a finished car in the final assembly factory. The product range includes the car models V70, XC70, XC90, V60, V60-hybrid, S60 and S80. All different product variants are more or less produced on the same flexible line through the whole production plant.

4.1 The body shop

The production of a car body starts with the under body, which is the flooring structure. The under body is manufactured in three different parts, the front, middle and rear, which is thereafter welded together into the complete under body and sent to a under body buffer. When the very first front part of the under body is manufactured, the product receives an identity and specifications for further manufacturing.

When the under body leaves the under body buffer it enters the area on which the thesis is focused. The order queue is already set, so the loading station after the under body buffer selects the right product and loads it on a fitting pallet type. Numerous operations of respot welding and assemblies of left and right sides, roof beams and a roof as well as several quality checks leads the product into the K10 buffer. When the product enters the K10 buffer it leaves the thesis's area of interest. The XC90 model has an almost entirely independent flow through the body shop, and it does not cross the thesis's delimited area between the under body buffer and K10.

After the K10 buffer the products go through further assembly lines with components such as fenders and doors, before they are sent off to the paint shop. Once the products have been painted they continue into the final assembly, where the products receive all their interior and external details before they are quality tested.

5. PROCESS MAPPING AND PRIORITIZATION OF PROBLEM AREAS

This chapter is divided into seven main sections. Firstly the problem definition is described under section *5.1 Problem definition and Project plan,* thereafter the studied literature are presented under section *5.2 Establishing of theoretical* foundation. The results from the process mapping are presented in section *5.3 Conceptual Modelling and Process Mapping*, and thereafter follows the geographical modularisation under section *5.4 Modularisation of the production system*. The execution and results from the static analysis on module level can be found in section *5.5 Initial static analysis*, whilst the performed interviews are described under section *5.6 Interviews*. A prioritization of certain points of interest is stated in section *5.7 Prioritization list.* After the prioritization was set the analysis continued with focus on the areas of interest, see chapter *6. Analysis of System Losses.*

The thesis has followed the outline displayed in figure 11, which is an overview of the execution of the thesis. As seen in the figure the thesis has followed an iterative methodology where conclusions have been drawn after each step which have justified in which direction the next steps are taken.

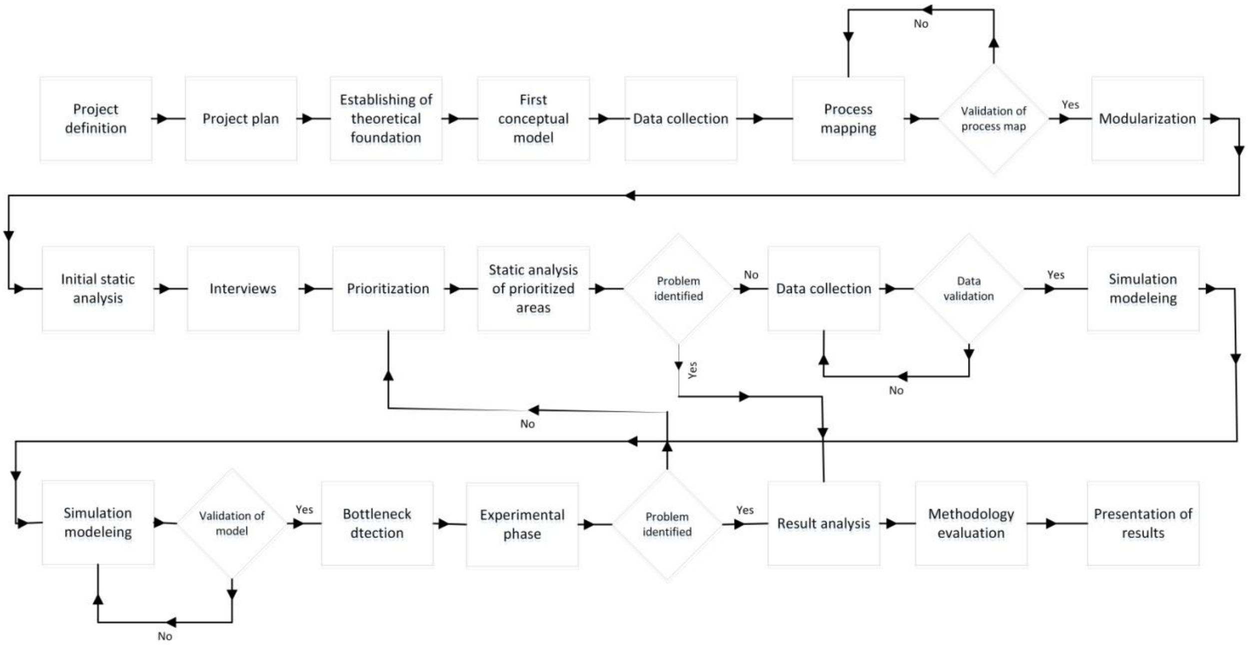

Figure 11, map of the execution of the thesis.

5.1 Problem definition and project plan

The problem definition was made in cooperation with tutors at Volvo Cars Torslanda (VCT) and Chalmers University of Technology. Discussions led to the research questions in section 1.4 *Problem formulation*. As a result of the problem definition a project planning report was written and thereafter approved by VCT and Chalmers University of Technology. The project planning report included a problem context, the aim of the thesis, limitations, the research questions and a time plan. The time plan in the form of a Gantt-scheme.

5.2 Establishing of theoretical foundation

In order to scrutinize the given main problem and come up with significant theories and methods literature within relevant subjects was studied in an initial phase of the thesis. The studied literatures were mainly within the subjects of data collection, process- and value stream mapping, bottleneck detection methods and discrete event simulation. Basic knowledge about production systems are gathered from courses taken at Chalmers University of Technology, such as Lean Production, Production Management and various project courses which include simulation. Deeper knowledge within the subjects was gathered through researches in books, scientific articles and PhD theses. Inspiration and information were also collected through previous master's theses within the subject. All the theories used in this project are described in chapter *2. Theory*.

5.3 Conceptual modelling and process mapping

As explained in section *4.3 Conceptual Modelling and Process Mapping* the process mapping was chosen to follow the construction of a Value Stream Map (VSM). The product group was set to include the car models that are produced within the limited area of the body shop: S60, V60, V70, XC70 and S80. The level of detail on the VSM was chosen to be at a station level within the thesis geographical limitations, see figure 2 on page 2. This decision was based on the fact that most data were collected at a station level. In addition to the VSM over the limited geographical area, a VSM map over the whole body shop at a line level was constructed in order to get an overall picture of the flow, and especially the information flow.

When product group and level of detail had been chosen rough sketches of the body shop's flow were drawn from existing maps in order to get a first view of the plant. These maps worked as first conceptual models and guidance in the following process mapping. Before the site visit a number of main data parameters were constructed, these were:

- Model specific cycle times
- Transport times
- Number of pallets for each pallet type
- Available production time
- Planned downtime
- Downtime
- Change over time

Focus was on these data parameters when the mapping at the floor was performed. The mapping was performed by walking upstream from the last station to the first station. Starting on line level through the whole flow in the body shop and then at a station level within the limited geographical area. Some data were collected during the mapping in order to get an estimation of the different times and not in order to create statistical foundation. In addition to the site visits short interviews were held with a number of experienced people in order to get a clearer picture of the information- and material flow and the overall manufacturing process. The VSMs were continuously reconstructed after several site visits and interviews until all relevant information were included and the map was thoroughly validated.

The two different VSMs, on line level and on station level, were created in Microsoft Visio with standardized VSM icons and data gathered from VCT's databases. Conclusions were drawn that a VSM classical snapshot picture would not contribute to a satisfying enough level of detail for the analysis of the process, due to the large variations in the flow. Larger amounts of data were required; therefore historical data were collected in VCT's databases and not during the mapping. The collected data were weighted in relation to the product mix in order to get a representative average for each station to ease the analysis and create a fair picture of the production.

When interviews, observations and data had been gathered, analysed and visualised in the two VSMs, the conceptual model was validated through interviews with knowledgeable people. The resulting two Value Stream Maps are presented below in figure 12 and figure 13. Figure 12 show the entire body shop on a production line level, whilst figure 13 illustrates the VSM on a station level within the area of interest specified in figure 2 at page 2.

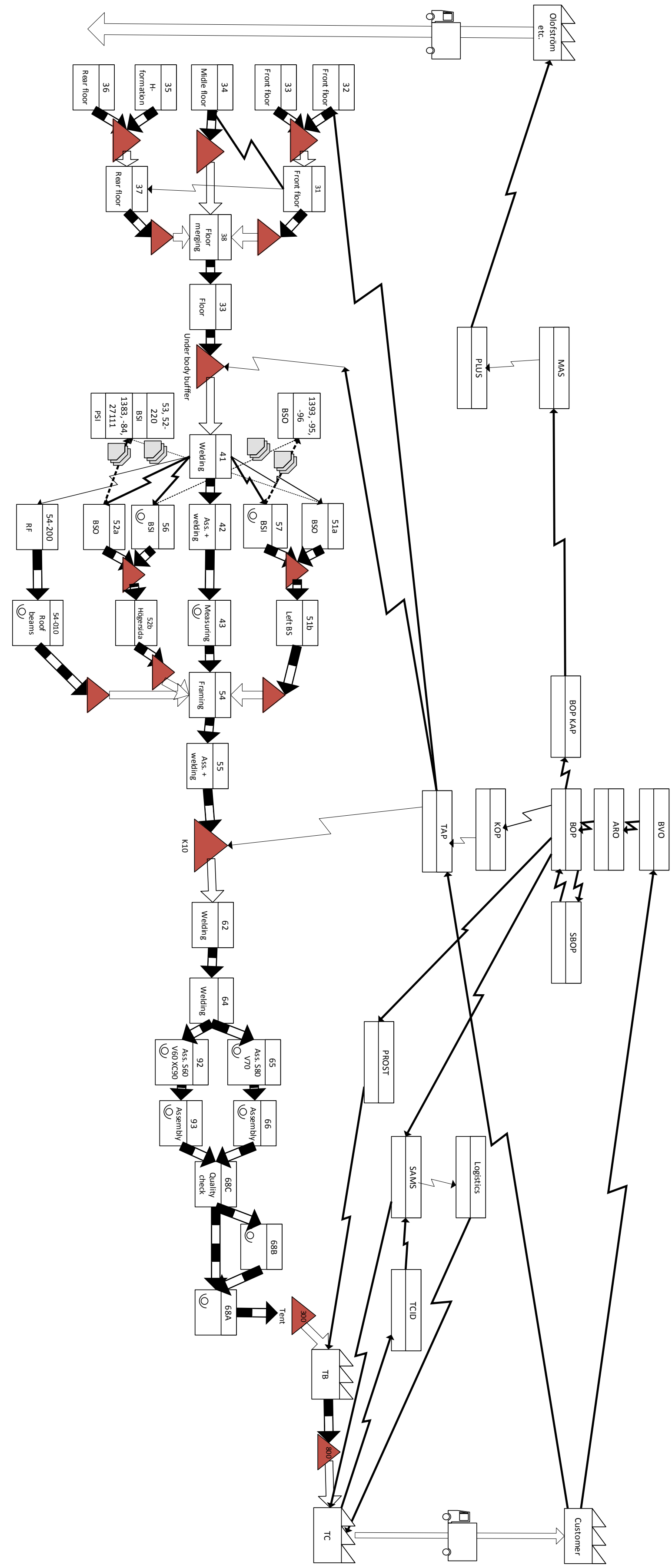

Figure 12, VSM over the entire body shop

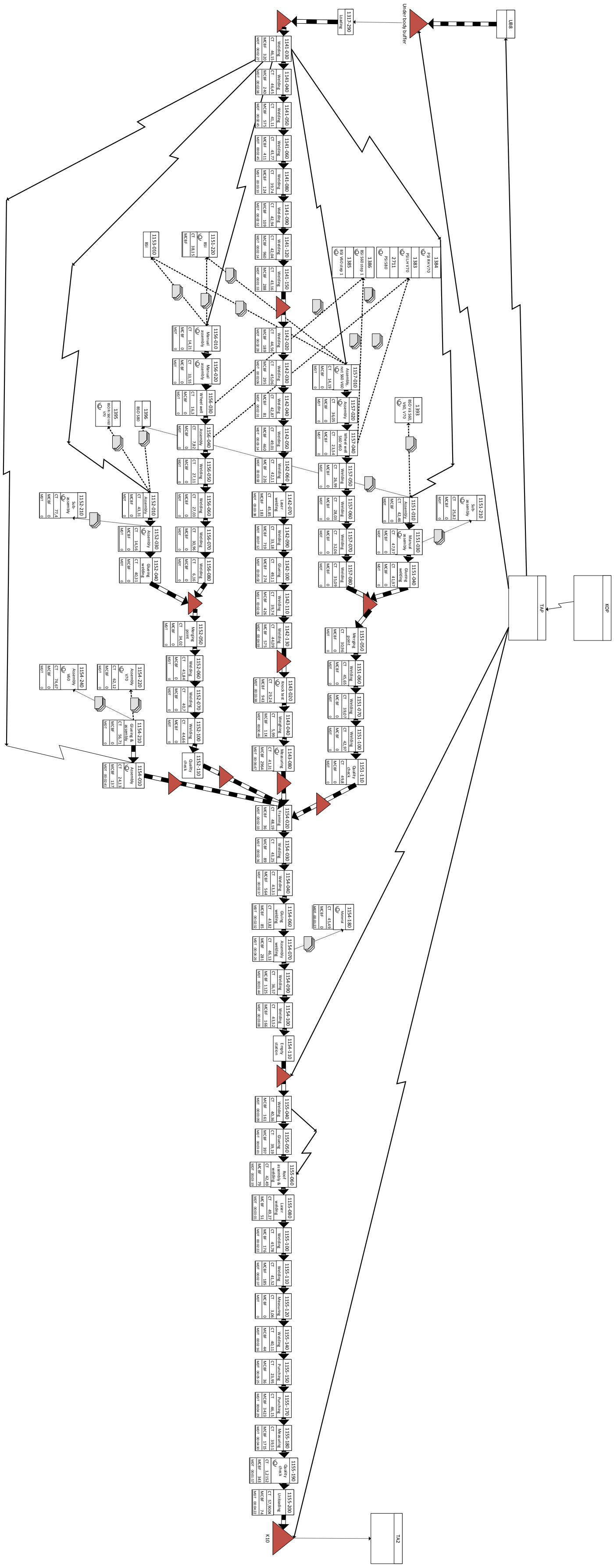

Figure 13, Value Stream Map over the area within the thesis limitations.

As figure 12 illustrates, the information flow for the body shop is very complex. It can also be noted in both figure 12 and figure 13 that there are many buffers in the system, in fact there are even more buffer places than displayed in the figures, due to the many transportations in-between stations and production lines.

5.4 Modularisation of the production system

When the process mapping was finished all of the stations were divided into six different modules. The modules were set based on the complexity of the stations within the module and how they affect the overall system. All the chosen modules have some buffer capacity between each other, and some have internal buffer places.

Module one were decided to consists of the two first production lines, 11-41 and 11-42, since they mainly consist of respot robots and are relatively stable. Module two consists of the third production line, 11-43, which is a measurement line. The measurements are not done the same way on all products which generates differences in cycle times on this production line. Module three and four consists of left body side (11-52 and 11-57) and right body side (11-52 and 11-56), which are divided into different modules since the production is affected unequally by the two sides. The fifth module consists of the production of the roof beams and ringframe (11-54) and the sixth module handles the line from the framing of the different lines downstream to the K10 buffer (11-54, 11-55). The different modules have been visualized in figure 14 below.

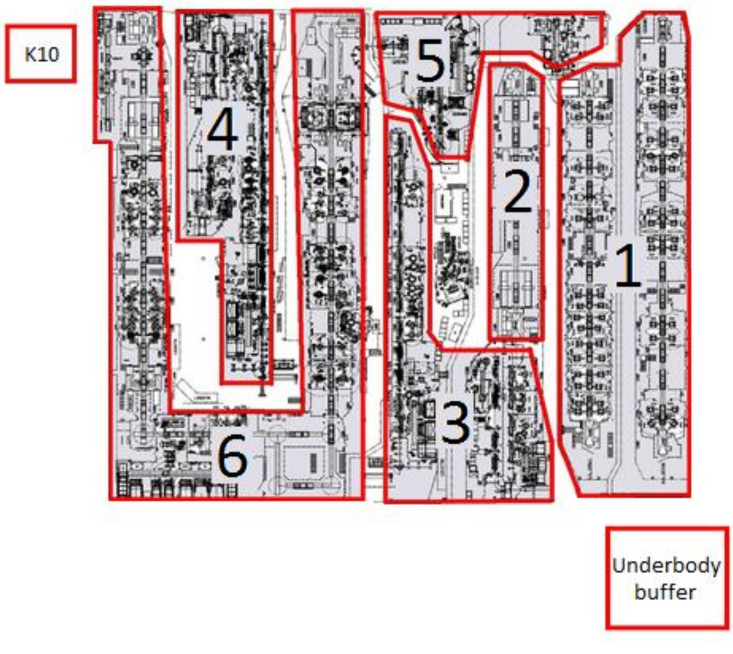

Figure 14, modularization of the chosen area in the body shop.

5.5 Initial static analysis

The static analysis was performed in two steps, one initial in order to come up with a prioritization of the problem area due to the rather large amount of stations within the system, and a second at a higher level of detail for the prioritized areas, further explained in section *5.7 Prioritization list*. The static analysis was based on the conceptual models, observations, data and interviews.

In the initial phase analyses based on cycle times and throughput rate were combined with disruption analyses in order to find the bottleneck or the problem area. These analyses were mainly performed on module level, see section *5.4 Modularisation of the production system* for description of the modules. However, all stations' inherent cycle times within the system were collected and analysed since they are of interest in the bottleneck detection analysis.

In the following sections the analysed data are presented and classified according to the three categories mentioned in section *2.3 Data collection*; Category A - Available, Category B - Not available but collectible and Category C - Neither available nor collectible. Several databases with different ways of logging the data have been used in order to get as correct data as possible and in order to verify the data properly. Before the data were collected the level of detail was considered. As mentioned above some data needed to be collected on station level and some needed to be collected on module level.

Times which were not available in databases had to be collected manually by timing the missing events. This data therefore belong to Category B - Not available but collectible. Fortunately these times were mostly transport times, elevators and turntables, which could all be assumed not to depend on different car body models. However, these times were noted to vary for different pallets, so approximately 10 events were timed in order to calculate a reliable average time (with extreme values excluded).

5.5.1 Inherent cycle times

Inherent cycle times, or machining times, for the different stations in the production flow could be categorized into A - Available. At any given moment the duration of the approximately 15 000 latest historical cycles, which is approximately 40 days of production, could be extracted from a logging system called CTView and imported into Microsoft Excel. Thereafter the cycle times were separated into the different car models and a weighted average for each station and model was calculated. When calculating the average cycle times the extreme values were removed since they could be assumed to be incorrect.

A problem with the CTView logging system is that machines tended by operators do not log the full inherent cycle times, only machining times, which could yield a misleading cycle time analysis. As an example one station's cycle time indicated that the station worked well under the cycle times of preceding and following stations, but one look at the disruption log instantly revealed that the cycle times for the station were often exceeded. These stations cycle times needed to be validated by timing the processes manually. Furthermore, for every observed station there were several car bodies of unknown model with registered cycle times. These have however been considered negligible due to their low frequency and have therefore been excluded. The results of the cycle time analysis are presented below in figure 15.

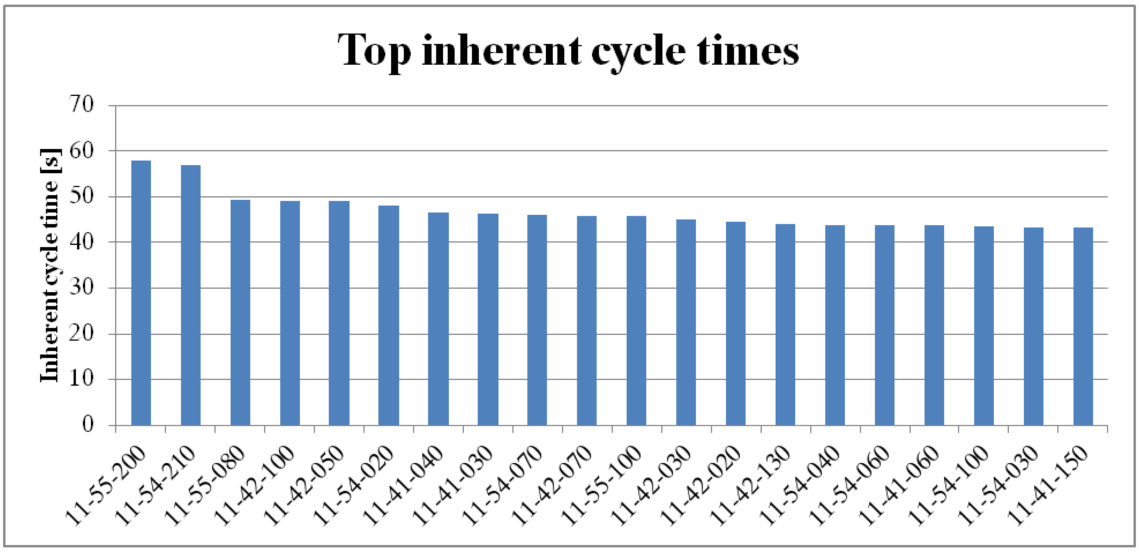

Figure 15, the stations with the top inherent cycle times.

Figure 15 presents the stations with the highest inherent cycle times in the system. VCC's takt time is at 60 seconds, as seen in figure 15 all stations' inherent cycle times are below 60 seconds which make them acceptable. The problem did not seem to be the inherent cycle times.

5.5.2 Throughput rate

Throughput times were extracted from the production control database (TAP), thus categorised into A - Available. Data for the first and last station of all modules were extracted for three representative days. The number of car bodies that had passed the stations between 07:00 and 17:00 were selected and the throughput time in seconds per unit were calculated for first and last stations within each module and graphically visualized in figure 16 below. The lighter bars illustrate the three connecting flows, the left body side 11-51-100 (module three), the right body side 11-52-100 (module four) and the roof beams 11-54-010 (module five), whilst the darker bars all indicate the under body flow (module one, two and six).

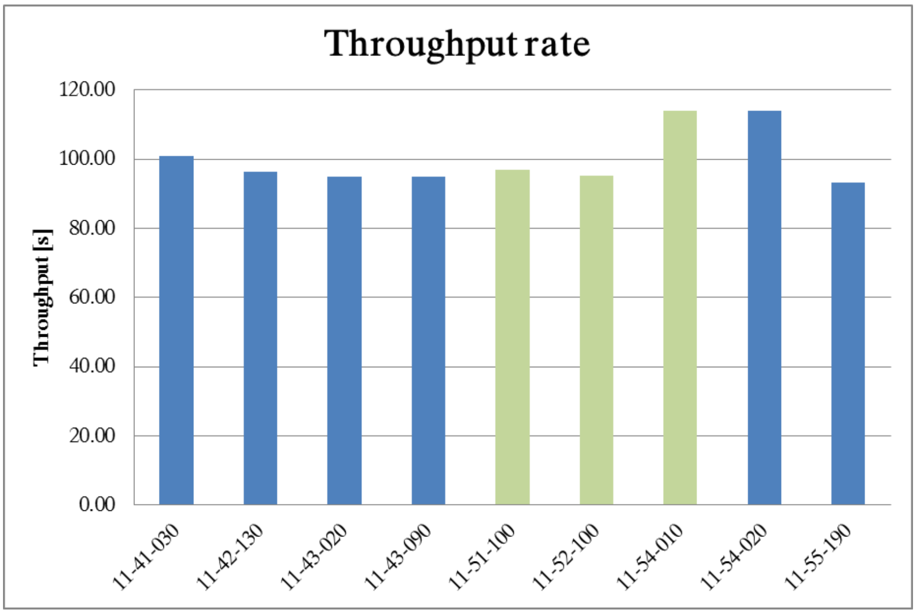

Figure 16, throughput rate.

In a system the throughput should be somewhat the same for all connected stations, but due to the fact that all stations are not always occupied some stations register a faster throughput simply because they had a better starting point with a larger work in process. This effect is enlarged since only three days have been studied, but overall the throughput time for the production flow is accurate.

According to figure 16 station 54-010, in module five, seems to limit the framing station 54-020, which is in the beginning of module six. Noteworthy is that this limitation of the flow do not extend to limit station 55-190, which is located at the end of module six, as it should when the stations are connected to each other. However, this could as discussed above be a result of the short period of time that is considered. Furthermore, it is remarkable that the throughput rate is at approximately 95 seconds when the inherent cycle times for the stations are well below 60. This indicates that the problem is not the cycle times but down times, transport times or something else.

5.5.3 Production disturbances

The analysis continued with studying the disturbances, primarily to see whether the high throughput times were a result of the disturbances, but also in order to visualise the system constraints. Data on downtime, starvations and blockings for each station could be extracted from VCT's database for disturbances (SUSA), hence categorised in to A-Available .

When searching for the system constraints the common utilisation method, see section *2.4.1 Bottleneck detection methods*, could not be used since the active time could not be specified accurately. Unfortunately only disturbances are logged and there is no way to know for certain when the station has been active or not. Therefore a modified version of the waiting time method, see section *2.4.1 Bottleneck detection methods*, was developed based on available data. Instead of studying where products have to wait the longest, an analysis of whether each station is starved or blocked the most could be executed.

The database (SUSA) was unfortunately not optimal for the cause. The database records the lengths of disruptions in seconds and the first alarm owns the recording at the specific station, while hiding all simultaneous underlying disturbances. When the first disturbance settles an underlying disturbance can take ownership, but the time for the second disturbance is not the true duration since its beginning is hidden from the first disturbance. This would not be a problem if all disturbances led to a halt in the process, but at the time being only some do and this leads to inaccuracies in the calculations.

Another issue with the database is the times displayed for short stoppages. The database receives its data from a Virtual Device which checks the Programmable Logic Controller (PLC) for a status change only every 25th second. This means that a shorter disturbance which starts and resolves within the 25 seconds is not recorded; whilst some short disruptions which take place during a status check are recorded. This leads to a very random recording of small disruptions.

Yet another quite unpredicted problem with the database is that only some interruptions are actually logged in the system. The system (SUSA) looks at predefined codes and selects which status changes to log, leaving others behind. There are standardisations for this but they have not been followed, which led to the discovery of some interruptions that were logged in the short memory of a PLC but not in the database. The effects of this problem are very hard to grasp, but it can only be assumed that the database is relatively close to the truth since it is the only system VCT uses to log and follow up disturbances.

Furthermore, data for the first and the last stations were not always able to be collected since not all stations recorded information in the system. In module three and four nearby stations needed to be chosen instead of the last ones. This problem was considered negligible due to the fact that the stations that were chosen were nearby and directly linked to the last station in the module. Furthermore, in module three and four the first stations were excluded from the initial study since they do not affect the main flow directly. There are several starting points for module three and four where the first material is mounted. It could be assumed that the last stations would indicate problems within these modules.

The disturbance times were verified in a couple of strategically selected stations by comparing them to the production control database (TAP). An average inherent cycle time, weighted by car model, was multiplied with the number of produced car bodies in order to generate the process time. Thereafter the process time was summed with the calculated disturbance time and then compared to the overall production time for the time period. The added process time and disturbance time normally reach only 70-80% of the overall production time, which could be explained with transport times and product handling in between the processes.

Data from each module as well as station 11-73-680, where the under body is loaded into the pallet, were extracted for the last 32 days of production in order to evaluate the modules, see figure 17 below. A clarifying flowchart of the studied stations is displayed in figure 18. To assure representative data the activities during the night shift were removed. The takt time is much lower during the night shift, which creates many starvations and blockings due to the simple fact that fewer products are in process. All data recorded during brakes were also removed since the manual stations generate starvations and blockings in the production system during break times.

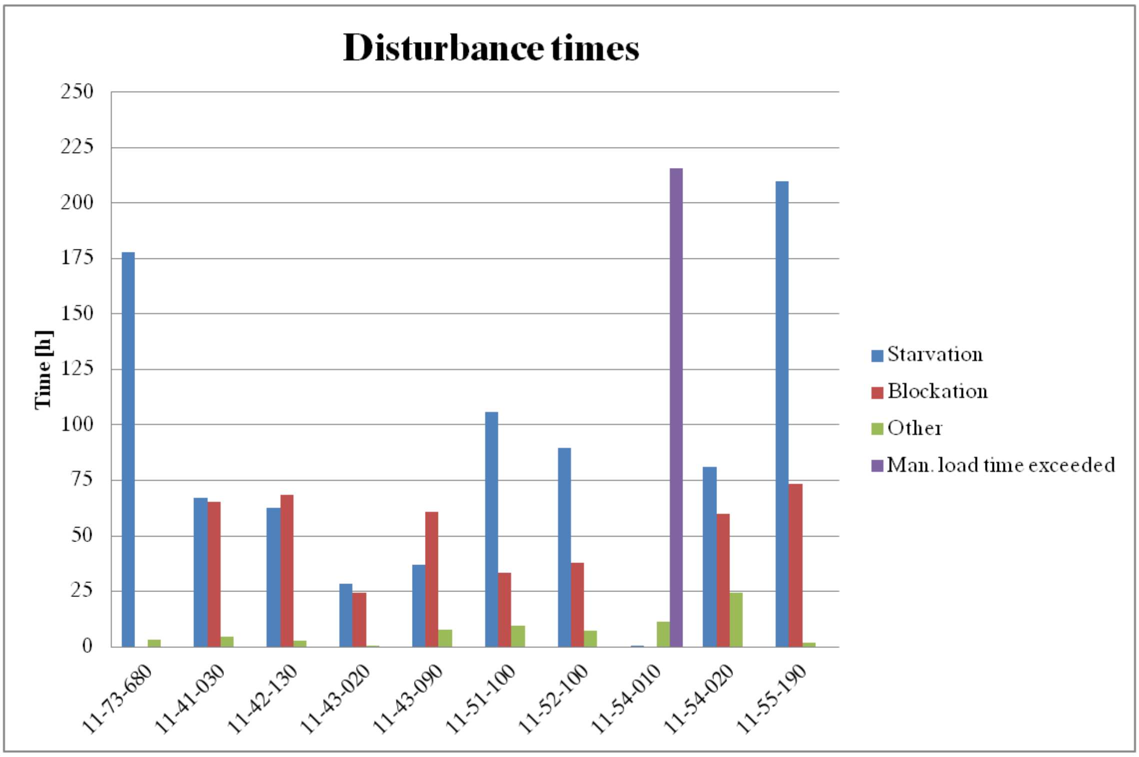

Figure 17, disturbance times on module level.

Figure 17 illustrates that module one and two (with end stations 11-41-130 and 11-43-090) are generally more often blocked than starved, which indicates that the bottleneck lies downstream in the flow. However in module five and six (with starting stations 11-54-010 and 11-54-020) the starvation times are higher than the blockings, which raises a suspicion that the constraint in the system is near the framing station 11-54-020, or somewhere downstream from that point. It was also noted that the framing station had the largest rate of "Other" disturbances, which are inherent disturbances and not waiting times. When it comes to module three and four (11-51-100 and 11-52-100), the left and right body side, it seemed as their constraint lies upstream in their respective flows.

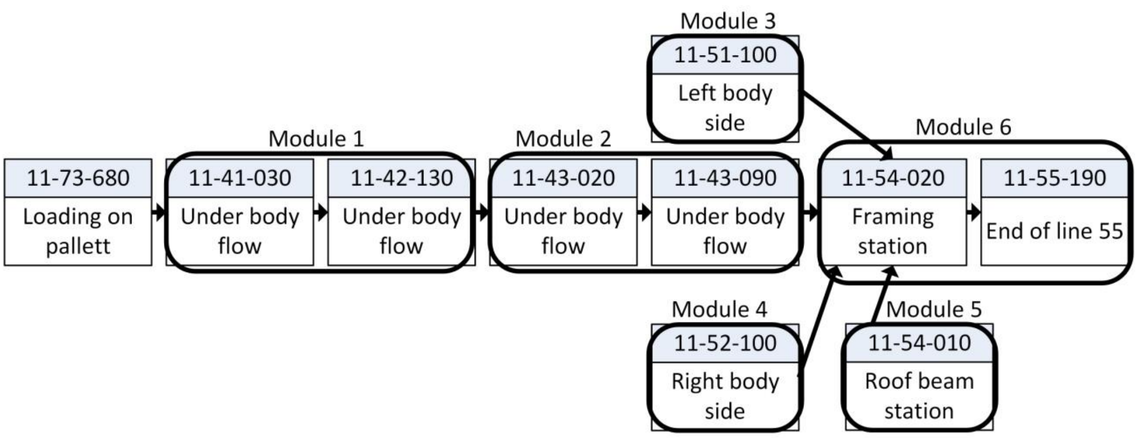

Figure 18, flow chart of the studied modules.

It is notable that the starvation times as well as the blocking times are in close relations with the cycle times. For example station 11-73-680 and station 11-55-190 in figure 17 above are both known to have at much lower than average cycle time. This means that when these fast stations have finished their processes and are ready to start new ones, they have to log starvation due to slower preceding stations. However, the relatively fast stations should also log blockings just as quickly, which means that a comparison between starvation times and blocking times within the fast stations should point in the direction of a bottleneck. Another interesting aspect is that the disturbance “manual loading time exceeded” appeared a lot in the roof beam station 11-54-010 (module five), which needed further investigation.

The same analysis was performed for the framing station 11-54-020, where the four flows merge into one in the beginning of module six. This station’s starvation and blocking disturbances indicate which out of the four flows the framing station is waiting for or blocked by. The results are illustrated in figure 19 and figure 20 below.

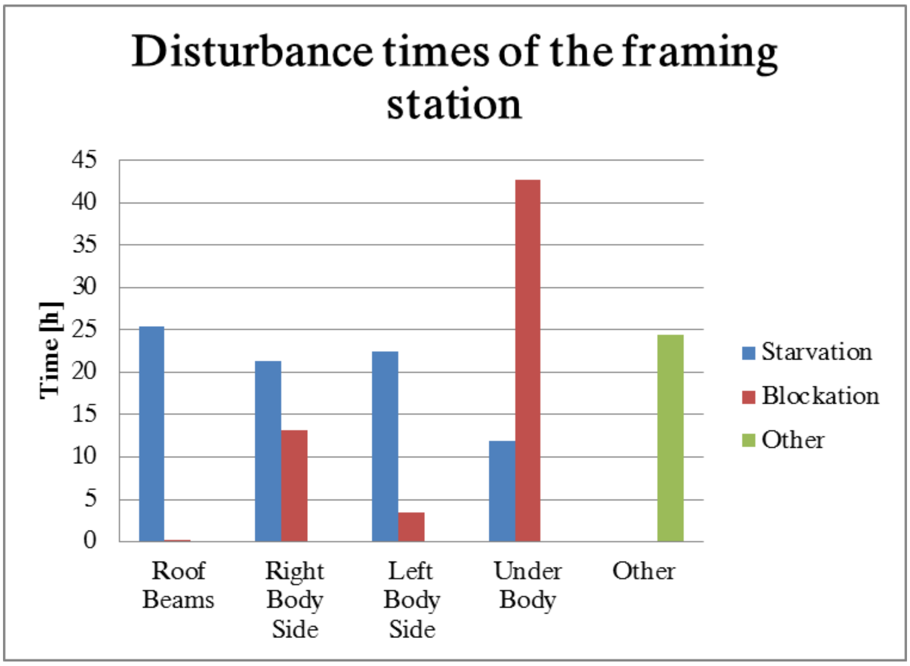

Figure 19, disturbance times for the framing station.

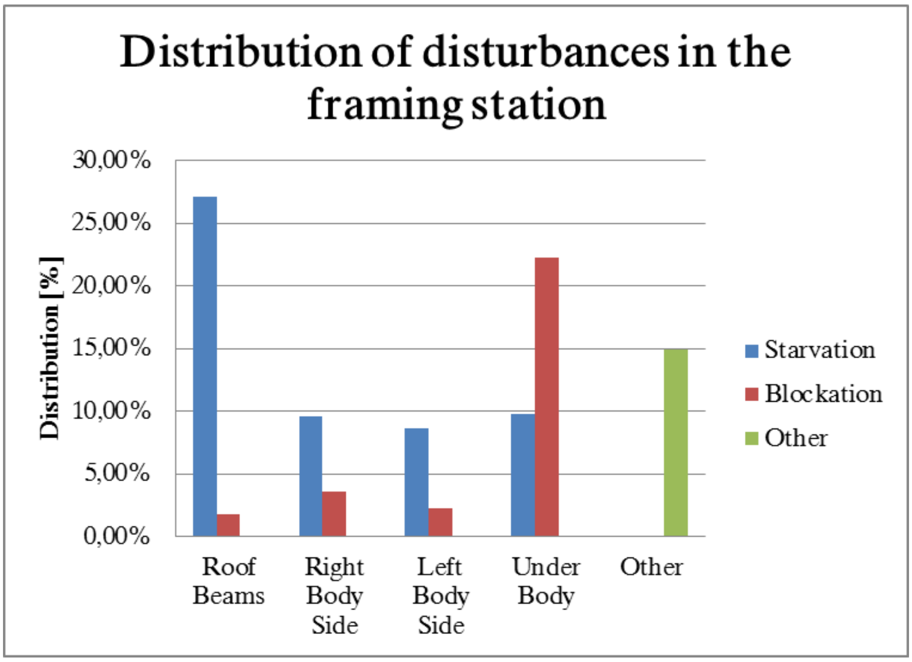

Figure 20, distribution of disturbances in the framing station.

Figure 19 and 20 clearly states that the framing station is mainly starved waiting for roof beams, “Roof Beams” which is module five, and blocked by the downstream under body flow, ”Under Body” which is module six. Note that when looking at the number of disturbances the roof beam station has a clear majority of nearly 39%. This supports figure 17, where the roof beam station 11-54-010 logged many disturbances under the title “manual loading time exceeded”. It became clear that the roof beam station, which is module five, needed further research and so did the downstream under body flow, module six, with the framing station and its relatively large bar of “Other” disturbances.

5.5.4 Transport times

In order to make sure that the transport times do not constraint the production system they were extracted from two different databases and also gathered manually, hence the classification of data as both A - Available and B - Not available but collectable. The transport times for stations that had a predecessor on the same production line were extracted from the same database as the cycle times (CTView), hence based on 15 000 cycles with extreme values excluded. Transport times between lines and for stations without logged cycle times had to be extracted from another system (TAP) that logged passing bodies. By comparing time stamps for individual bodies the missing transport times were calculated. These calculations gave average transport times independent of car model and were based on over 5000 car bodies with extreme values excluded.

The system that log cycle and transport times (CTView) is not thoroughly standardized and placement of recording equipment as well as the information system itself could differ between stations. The fact that two different databases have been used to calculate transport times are another source for uncertainty since the two systems collect data differently. Further uncertainty lies in whether the whole transport time is included or not and how the transport time is defined in the system.

However, the data could be validated by timing a number of strategically chosen stations by hand and comparing those times with the two databases’ recordings, both by validating the mean value and by validating the logged data. Stations without recorded data were also timed by hand, in these cases the timing was based on approximately 10 passing bodies, which were considered sufficient due to the low variations in transport times. The transport times were also verified using the production control database (TAP) and calculating lead times, which are the sum of previously calculated cycle times and the transport times.

The transport times were checked over in search for large variations in speed or distance. All times gathered were found to be below the takt time of 60 seconds, and should therefore not constrain the production system. However together with the cycle times the takt time could be exceeded, so the transport times are still of importance.

5.6 Interviews

Interviews were held with selected people in order to identify problem areas and to get a comprehensive knowledge of the different problems in the factory. They were also used to validate and discuss the identified problem areas from the static analysis. The persons whom were chosen for the interviews were from different departments and had different work tasks, they were for example mechanics, engineers and managers. This gave a width and comprehensive knowledge and more trustworthy results.

The same questionnaire, which can be found in appendix A, was used during all interviews in order to be able to compare and analyse the different answers. The interviews started with wide and comprehensive questions in order to not influence the interviewee and then became more and more specific in order to validate the information that was extracted from the static analysis. More specific questions within the interviewees work area were also discussed at the end of each interview. During the interviews maps were used in order to easier illustrate and discuss geographical areas and pinpoint problem areas. Graphs from the static analysis and the process maps, were also presented to the interviewee in order to get new perspectives, a relevant discussion on the static analysis and a validation of both the analysis and the process maps.

All ideas of different problem areas that came up during the interviews were gathered and analysed continuously as the interviews proceeded. It soon appeared that some ideas were shared throughout the group of interviewees, some were shared within departments and some ideas were unique. Ideas which supported the analysed data were of extra interest but also frequent ideas were considered a resource and later on compared with further data analysis. The ideas that were unique and poorly founded were shelved. The ideas from the interviews were stored in an idea database. This database also consisted of different ideas that were collected through the project, both from different persons and ideas resulting from the different static analyses.

The ideas that were considered solid and well founded followed a pattern and could therefore be categorized into eleven different categories. The results from the interviews were visually compiled in a graph, see figure 21 below.

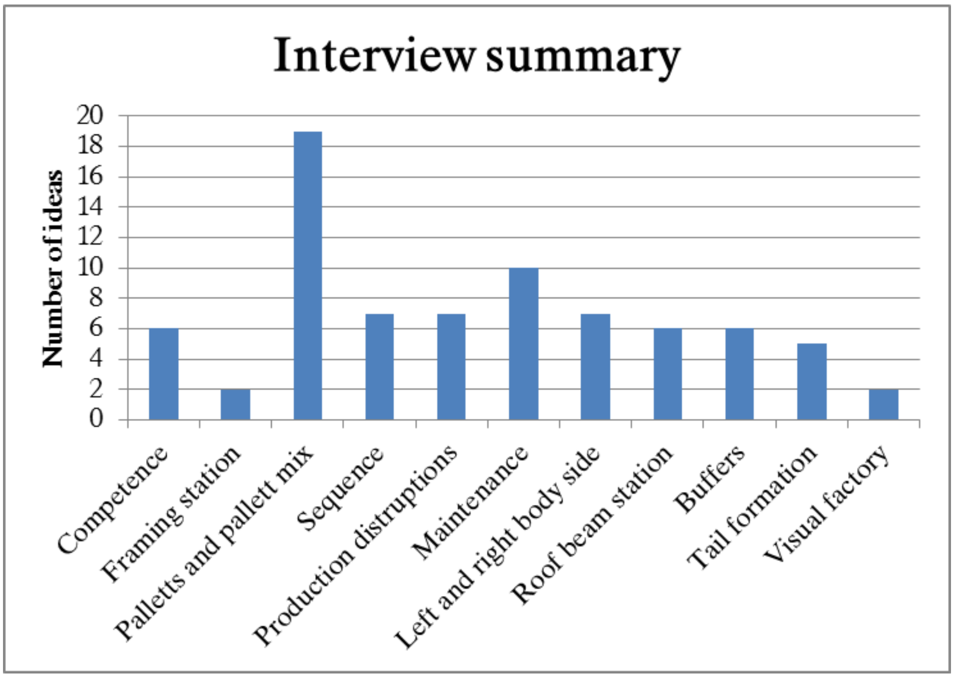

Figure 21, overview of the number of ideas per problem areas from the interviews.

It is rather hard to draw conclusions of figure 21 since the different ideas within each category could have different likeliness and value for the project. Furthermore, the graphs consist of both unique ideas and ideas shared between interviewees. However, the figure does point out areas that are of interest to evaluate further since a number of knowledgeable employees pinpointed different problems within the area. Generally the interviewee tended to favour problems within his/her area of expertise, but a fair distribution over the different problem areas were accomplished since the interviewees were from different departments and had different areas of expertise.

As seen in figure 21 the pallets and mix of pallets is overrepresented, this result came from the fact that many of the interviewees mentioned problems with the mix of pallets, mainly that it is hard to get the mix right. Other comments from the interviewees on the subject were: there are too few pallets, the system is highly sensitive, the wrong mix of pallets initiates empty pallets in the flow and that the wrong mix of pallets causes a tail formation that transplants through the flow. A tail formation means that intact queues transplants through the system and causes production waste in form of unutilized machines both before and after the queue. Another comment is that these queues also result in that it takes hours to normalize the flow after a production breakdown.

Comments about the maintenance mostly handled that the maintenance of the equipment is not synchronized but appears stochastic which in some cases interfere on the production. This category is also closely related to the category visual factory that handle the difficulties to see were in the factory a problem have occurred. A general opinion of many of the interviewees was that the framing station is a bottleneck, not many could however identify a problem area within the framing station. The two identified problems within this category are the high level of disruptions at the framing station, which is located in the beginning of module six, and shortage of supply to the station. Many of the categories in figure 21 are self-explaining, quite many interviewees thought that the low output rate depended on the many production disruptions and problems with the right and left body side, and equally many believed that a pre-determined sequence could result in a higher output rate.

This categorization were later on combined with the results of the process mapping and further analysed in a static analysis, see chapter *6.1 Static analysis of module five and six*. Of relevance when selecting categories to move forward with were both the ideas that had the largest influence on the throughput of the system and the number of qualitative ideas within each category.

5.7 Prioritization list

Based on the static analysis, see section *5.5 Initial static analysis* and interviews, see section *5.6 Interviews*, a prioritization of the problem areas was made in order to set the focus for further analyses. The static analysis revealed geographical problem areas but more importantly in an initial phase it helped excluding areas of low priority with regard to the studied capacity problems. All points of interest, both based on interviews and static analysis, were sorted into categories including the geographical modules in section *5.4 Modularisation of the production system,* but also personnel qualifications, pallet flow, sequencing, production stoppages, maintenance and buffers.

When selecting categories to move forward with a qualitative evaluation, based on the categories that had the largest influence on the throughput of the system, was performed. This was a judgement call, since for example the qualifications of the personnel do influence the throughput of the system, but that is a question of developing the organization and does not fit within the thesis's limitations. The resulting list of priority is presented below.

- Pallet flow
- Module 6
- Module 5
- Product sequencing and/or batch production
- Production stoppages (including breaks, maintenance)

Based on observations, the interviews, see section *5.6 Interviews*, and the high degree of starvation in the loading station 11-73-680, where the car bodies are loaded on pallets, see figure 17, the pallet flow was given the highest priority. Closely after followed module six, which is production line 54 and 55, and module five, the roof beam station. These modules needed further investigation since the static analysis revealed that the system constraint most probably lies within these areas.

Based on the fact that the different car models have different cycle times, an analysis of whether a sequencing of the car models could yield in a higher system output would be of interest. Batch production could also be assumed to decrease maintenance and disturbances, since tool changes would be decreased. Finally production stoppages are a priority since for example break times in manual stations create queues in the production system which disturbs the flow.

The points of priority possess a high complexity and interaction both between each other and within the category. Thus they need to be related to different events and variations through time. Therefore, a dynamic analysis through a simulation study is preferred according to Carson II's (2005) list of situations when a simulation is suitable as mentioned in section *2.5 Simulation*. However, first the second and deeper static analysis of module five and six needed to be performed to assure that these important points will be simulated correctly.

6. ANALYSIS OF SYSTEM LOSSES

Now that the process mapping, the initial static analysis and the prioritization of problem areas, see section *6.7 Prioritization list* above, are finished the continued analyses could focus on the specific areas of interest. Further and more detailed static analyses, including a modified waiting time bottleneck detection, were performed on module five and six, see section *6.1 Static analysis of module five and six.* Thereafter the dynamic analysis began by modelling the delimited area of the body shop. See a description of the finished model as well as the results of the simulation, including bottleneck detection analyses, under section *6.2 Simulation results.*

6.1 Static analysis of module five and six

The prioritization, see section *6.7 Prioritization list* above, showed that module five and six, which is the roof beam station (54-010) and the production lines 54 and 55, needed to be analysed with a higher level of detail. Therefore a second static analysis was performed on each station within the modules.

6.1.1 Inherent cycle times for module five and six

As mentioned previously, the real cycle times for the different stations in the production flow could be categorized into A - Available. A second deeper cycle time analysis was performed on all stations within module five and six. This time with regard to the different car models, see figure 22 below for the average inherent cycle times of each station within the modules.

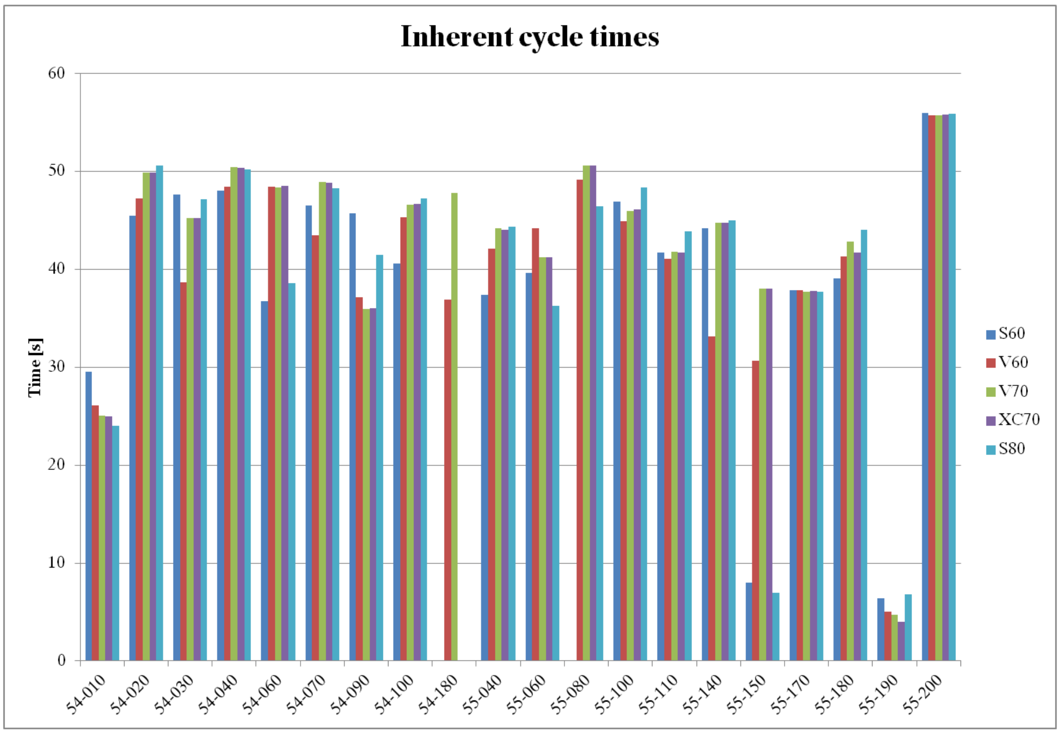

Figure 22, inherent cycle times for the stations on line 54 and 55.

It is noteworthy that all stations are below the takt time of 60 seconds. Station 55-200 stands out as the station with the highest inherent cycle time and is therefore of interest for further investigations. Another interesting aspect of the graph is that the different car models have some variations in cycle times, which indicates that model sequencing could save overall production time if at motivated sequencing could be found. This would however only increase the capacity of the entire production system if the cycle times were found to be the capacity constraint, which they are not. Batch production would decrease tool changes, which were found to not interfere with the cycle times, since the tool changes occur during the products transportation into the station. Therefore product sequencing and batch production were not considered priorities after this analysis.

6.1.2 Real cycle times for module five and six

Real cycle times for the different stations in the production flow could be categorized into A - Available. The inherent cycle time data came with a timestamp of when the recording took place and information about the product being processed, i.e. car model and main specifications. The time stamp was used to calculate the real cycle times, which were measured from when a car body is ready to leave the station until the next car body is ready to leave.

The real cycle times were compared with the inherent cycle times as well as with production reports on number of produced car bodies. The real cycle times were found to be very high, probably on account of the system losses in the production, since they include disturbances, transportation and other variations, not only the time when the station is working on the product.

It came to attention that CTView could miss recording cycle times when the PLC that send the recorded signal is busy. Several PLCs send signals on the same communication line, which means that from time to time the line is busy and a signal does not get through, which leads to missing recording of passing car bodies. In the beginning of the project this was a large uncertainty due to the fact that the number of registered cars did not match the production report, however when comparing CTView with the production report later in the project the problem had diminished dramatically, most likely since the system is continuously improved.

The real cycle times were verified using another data source called TAP. TAP is used for the production control in the factory and therefore register every passing car in each station. Except for some scrap products the number of cycle times did correspond to the production reports. The result of the analysis of the real cycle times is presented below in figure 23.

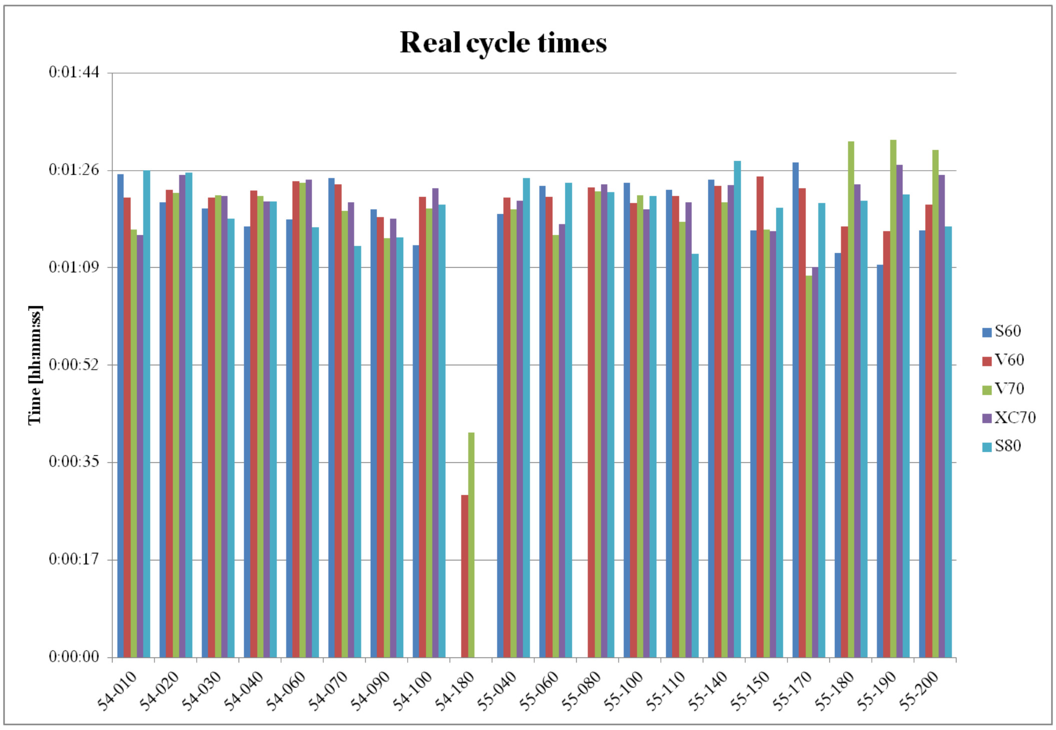

Figure 23, real cycle times for the stations on line 54 and 55.

As noted earlier under section *6.5.2 Throughput rate*, the systems takt time is far above 60 seconds. According to figure 23 the takt time on line 54 and 55 lies around 80 seconds. Together with the inherent cycle time analysis this concluded once more that the problem is not the inherent cycle times, but down times, transport times or something else that increases the takt time of the production system. In order to investigate the large differences between inherent and real cycle times the distribution of the real cycle times were illustrated in scatter plots, see figure 24 below.

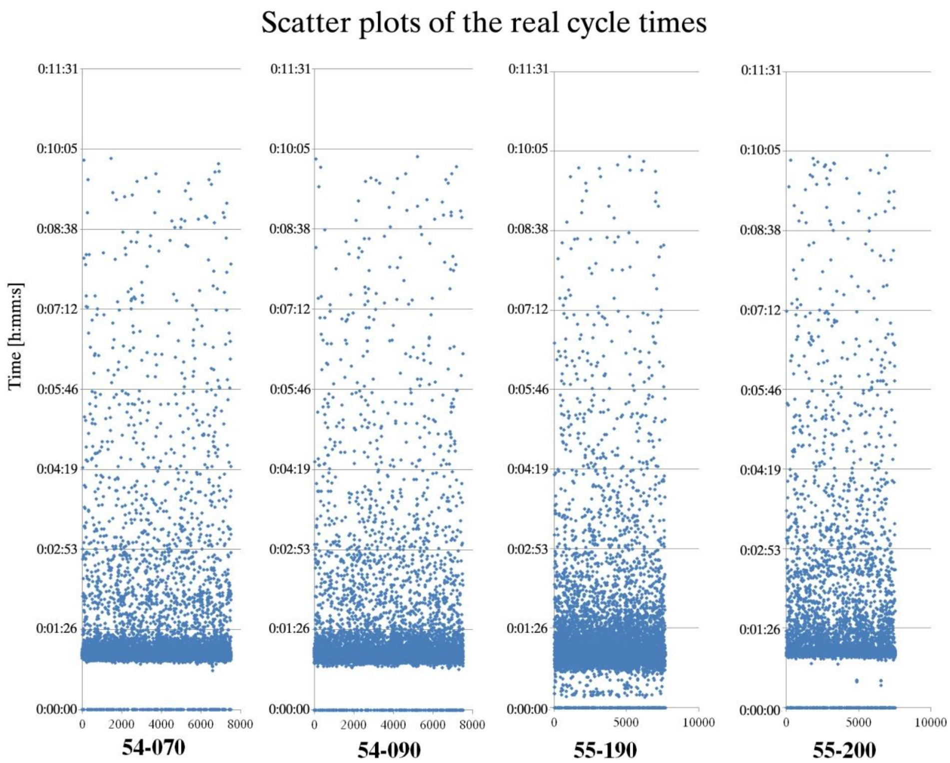

Figure 24, scatter plot of the real cycle times.

Cycle times over 10 minutes have been excluded in figure 24 above, which shows four representative stations, clearly states that many cycle times gather around 60 seconds, but the variations spread upwards toward much larger cycle times. However, the distribution seems to be evenly thinned from 60 seconds and upward so no extraordinary patterns were revealed.

6.1.3 Bottleneck detection in module five and six

Similarly as with the cycle times above, the disturbances at all stations in module five and six were calculated in this second phase of the static analysis, with the purpose of performing a static bottleneck detection using a modified waiting time method. In contrary to the previous calculations the brake times were not removed since it did not seem motivated with reference to the previous results. Automatic stations do not stop during breaks which mean that the disturbances that occurred during break time in the manual stations show up much later in automatic stations downstream. There is no accurate enough way to sort out the disturbances initiated by a break in a manual station from other disturbances. Calculations were carried out separately on both all disturbances and on the inherent disturbances, the results of which are displayed below in figure 25, 26 and figure 27.

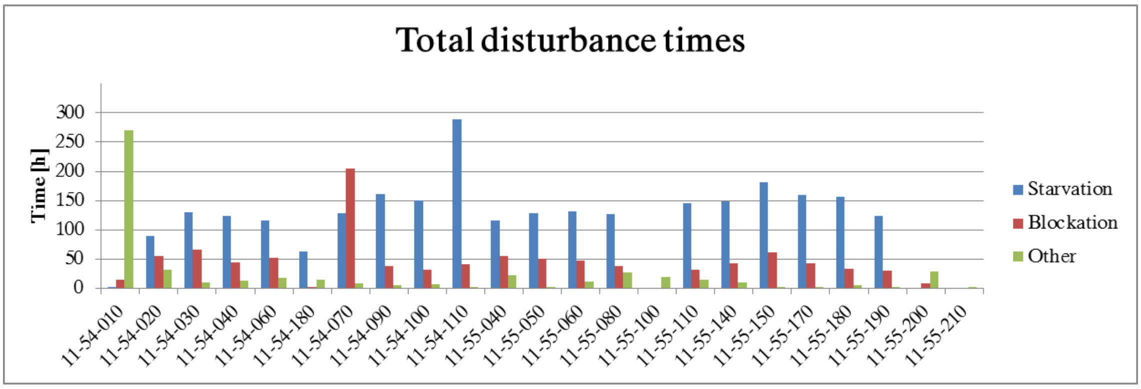

Figure 25, disturbance times at line 54 and 55.

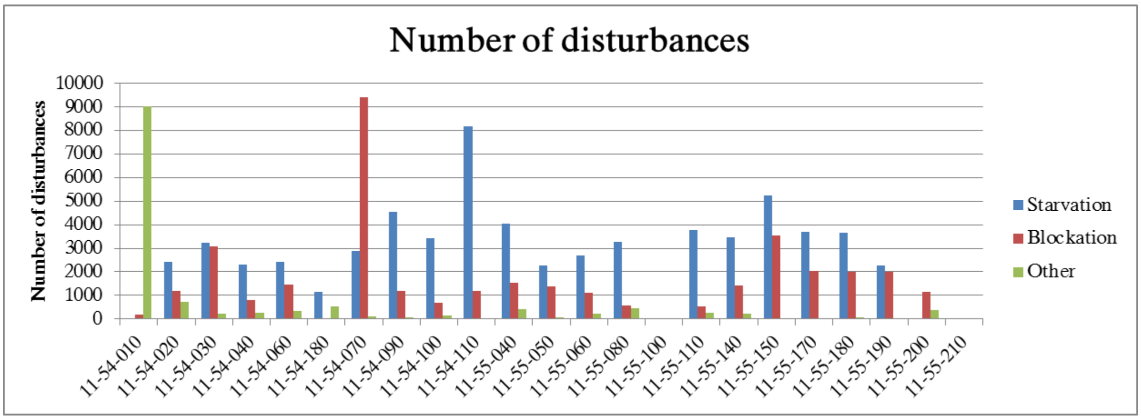

Figure 26, number disturbances at line 54 and 55.

The modified waiting time method for bottleneck detection performed on module five and six resulted in a deeper knowledge of the interdependence between the stations in the flow. The overall constraint seems to lie in the beginning of the line, based in the large degree of starvations on the line, but there is also a notable degree of blockings in the flow. It was also noted that station 11-54-010 have large inherent disturbances, see figure 25 and figure 26 above, though it came to attention that disturbances on this station could be double logged due to the setup of the logging system. The inherent disturbances would however still be large in comparison to the rest of the line if they were reduced to half their length. This station therefore has to be carefully validated and timed by hand before it is evaluated dynamically in a simulation model. The starvation times follow a wave like pattern with peaks at 54-030, 54-090, 54-110 and at 55-150. This could indicate trouble on the previous stations.

Station 11-54-070 adds a product part to only two of the car models, which leads to a very short cycle time for the car models which does not become processed in the station. This in turn leads to large blocking times forwards since the station is faster than the following station. A similar situation appears in station 11-54-110 since this station is an empty station before a small buffer area, which means that it has little or no cycle time and therefore becomes starved often. These phenomenons are also visualized due to the large number of disturbances.

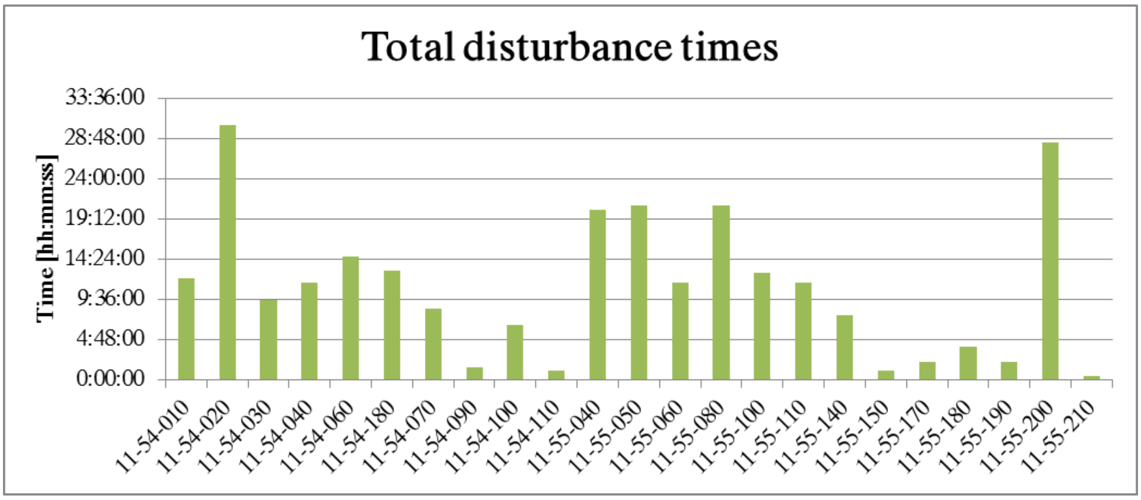

Figure 27, disturbance times at line 54 and 55

Figure 27 above illustrates the results of the inherent disturbance analysis on module five and six. It was discovered that station 11-54-010 logged the disturbance “manual loading time exceeded” as an inherent disturbance, even though it really is a sort of starvation or material disturbance. “Manual loading time exceeded” have therefore been removed from the graph above. This graph also follows a wave like pattern with exception for the peak in the beginning created by 11-54-020, the very complex framing station, and the peak in the end which is created by station 11-55-200 where the finished car body is lifted off the pallet and onto a skid before it is sent to the buffer K10.

When figure 25 above is put in relation to figure 27 (an enlargement of the disturbances marked as “other” in figure 25) it becomes clear that the waves of starvation and blocking appear in between the waves of inherent disturbances on the line, meaning that stations with high rate of inherent disturbances create larger starvation in following stations.

At this stage the static analyses were finished without any satisfying results and it was time to move on with a dynamic study of the productions system using a flow simulation, see section *5.9 Simulation results* below.

6.2 Simulation results

With the static analysis done and the prioritisation set the purpose of the simulation model became clear, thus the modelling could begin. The simulation modelling followed Banks (1998) guidelines described in section *2.5.3 The steps in a simulation study*. The problem formulation for the overall project, section *1.4 Problem formulation*, includes the two research questions, which the simulation model complied with:

RQ1 Which factors contribute to the system losses in the body shop?
RQ2 How much do the contributing factors affect the throughput in the delimited area of the body shop?

The objectives of the simulation model were based on the above problem formulation. The points of interest which were set during the prioritisation, section *4.10 Prioritization of problem areas,* definitely affect the capacity of the production, according to the static analysis, but how they contribute to the system losses is left to be evaluated.

The conceptual model started already with the VSM created during the process mapping, section *4.3 Conceptual Modelling and Process Mapping*, and have continuously grown whilst relevant data were studied and collected. During the interviews mentioned under section *4.8 Interviews*, the conceptual model was gradually approved by people with high knowledge of the system.

The next step was to translate the conceptual model into a computerized form by modelling the conceptual model in Plant Simulation, section *2.5.4 Plant simulation*. In this step the static model became dynamic when discrete events were added and the model behaviour became dependent upon time. The level of detail was set to vary according to the prioritization in section *4.10 Prioritization of problem areas.* For example; the pallet flow were carefully modelled with regard to its high priority and actions were taken to create a highly realistic representation of module five and six. At these modules was an empirical distribution of cycle times used in the simulation module, whilst for example module one and two were modelled with average weighted cycle times due to their relatively low priority.

6.2.1 Description of finished simulation model

The simulation model was built in accordance with the priorities stated under section *5.7 Prioritization list,* meaning that the points with highest priority were carefully modeled with a high level of detail and few assumptions were made. To assure that transport lengths and proportions were correct the building took place on top of a map which was to scale. For the pallets accumulated speeds were timed and entered into the model. The stations within module five and six received empirical distributions for their cycle times, based on each car model, whilst module one and two received weighted averages.

The under body buffer before the selected production area and the buffer K10 which is located directly after, were assumed to always be able to deliver car bodies and to always be able to receive car bodies respectively. This decision was based on figure 1 on page 1, which states that the under body buffer is nearly always full and K10 is nearly always empty. This assumption limits the reliable improvement potential of the simulation model, since the preceding and subsequent productions also will have to be able to increase their throughput.

As input for the model an order list based on 40 days of historical production was created. The product mix was based on mentioned order list, and thereafter the pallet mix was calculated with help from the person responsible for the pallet mix at VCT, in order to imitate the real system as accurately as possible. Today the delimited area of the body shop uses 81 pallets, of which 28 are V70 pallets and 47 are S60V60 pallets, which leaves only six remaining pallets for the model S80.

Mean cycles between failures (MCBF) and mean down time (MDT) was calculated for all station in the model, and thereafter converted into the form of availability based on operating time. MCBF was chosen over mean time between failures (MTBF) after discussion with knowledgeable people at VCT which concluded that the failures depend on number of cycles, and not on time. The availability was calculated according to the equation below:

$$Availability\ [\%] = \frac{MCBF \times CT}{(MCBF \times CT) + MDT}$$

Elevators were excluded from the availability calculations due to lack of data on disturbances, however VCT uses a template availability of 99,8 % for elevators, so this availability were introduced to all elevators in the model. Modelling to enable experiments on sequencing and batch production were not considered since they were written off during the deeper static analysis under section *5.8 Static analysis of module five and six*.

Production stoppages could still be entered into the model, but validation of the model could be done already at this stage when stoppages over 10 minutes were removed, see section *5.9.2 Simulation model verification and validation* below for further description of the validation. Also, it was considered easier to work with a steady state model first when evaluating the pallets and module five and six, and move on to include breaks, maintenance and night downtime at a later stage.

The connecting flows with the left and right body sides, module three and four, were not a priority and therefore they were only modelled to have an impact on the framing station, where they connect to module six. An empirical distribution of how often, counted in cycles, and how long the framing had to wait for a left or right body side respectively was entered into the model.

The simulation model was of course verified continuously through the construction, and once it was finished it could be validated. See section *5.9.2 Simulation model verification* *and validation* below for more information about how the model was verified and validated.

6.2.2 Simulation model verification and validation

The computerized model was verified throughout the modelling to assure that it worked as the conceptual model. Once it was confirmed that the model was verified the validation could begin. The validation process followed Sargent's (1984) recommendations as described in section *2.5.3 The steps in a simulation study,* with the production output as the main comparative factor, which also Banks (1998) suggest as a good method. Before the validation began the mix of products in the simulation model was defined to match a specific time period in the real factory, as described above in section *5.9.1 Description of the finished simulation model,* this in order to be able to compare the model to the real factory. Therefore the real factory's order list for 40 days was used as input in the model.

As described were the validation performed by comparing the model's output with the real factory's output. This was done by evaluate the output in jobs per hour, JPH, during the chosen time interval. The model was run for 40 days with 5 days of removed warm-up period. The mean value of the model's output were confirmed to 45,06 JPH based on 32 experiments, i.e. of 32 simulations that were run for 40 days were the average output 45,06 JPH. Calculations of how often a body leaves the real system were performed in the static analysis, with the result of one body leaving every 80 second, see section *4.8.2 Real cycle times for module five and six*. This calculation was also renewed and verified with the average throughput for the real factory using the models order list. This throughput results in 45,0 JPH for the real factory, which gives an error margin of 0,13 percent for the model which is a very satisfying result.

However, it is not only important that the outputs' mean value complies, the model's output also need to behave in accordance to the reality. Therefore, the distribution of the model's output in JPH were analysed and compared to the distribution of the real factory. This comparison also showed that the simulation model successfully represented reality. The simulation model's output over 40 days is illustrated in figure 28, and shows that the model's output has a stochastic distribution between approximately 20 and 55 JPH.

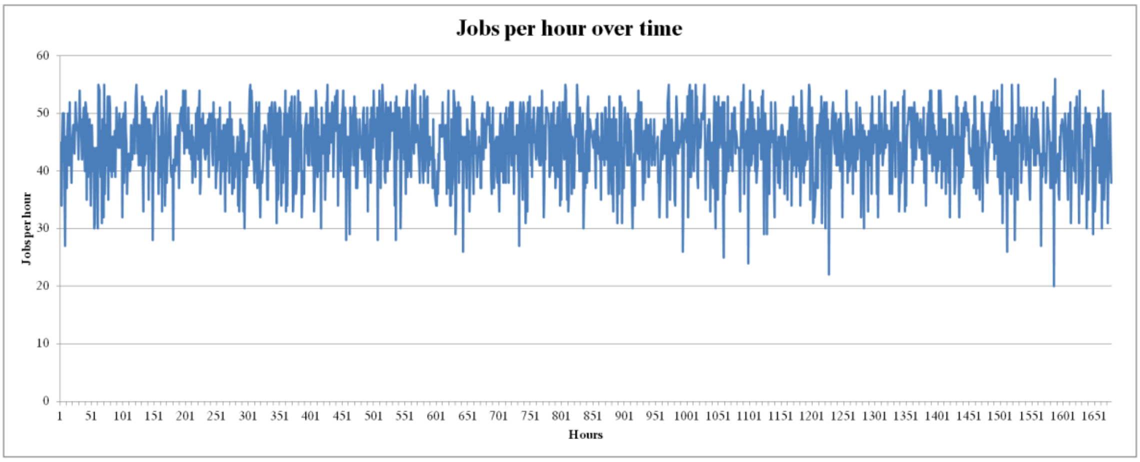

Figure 28, distribution of jobs per hour in the finished simulation model.

When the model's output had been successfully validated was further validation performed by presenting the model to knowledgeable people at VCT and by that make sure that it was a good visualization of the real system. When the model had been thoroughly validated it was approved for experiments.

6.2.3 Bottleneck detection

In order to decide which experiments that needed to be carried out a second bottleneck analysis was performed to be able to dynamic analyse the system and especially the pallets impact on the system. An evaluation of which bottleneck detection method to use were performed in accordance to Lima et al.'s (2008) methodology, where the fluctuation factor *elf* is calculated by number of stations involved divided by the sole bottleneck frequency per station, see chapter *2.4.1 Bottleneck detection methods* for further description. The calculations of sole bottleneck frequency were performed in the simulation model and based on 24 hours of production, with removed warm-up period, and the results for the 46 analyzed stations with a sole bottleneck frequency at 125 were:

$$elf = \frac{\sum station}{\sum_n^1 frequency} = \frac{46}{125} = 0{,}368$$

As seen in table 1 in chapter *2.4.1 Bottleneck detection methods* Lima et al. (2008) recommend to use the shifting bottleneck method when *elf* is below the value 0.5 since the system then has a high fluctuation with regards to the bottlenecks.
The shifting bottleneck analysis was also performed on 24 hours of production, with removed warm-up period. This limitation was done with regard to the large number of data that were needed to be processed. The shifting bottleneck method investigated which stations that are the momentary bottlenecks over a period of time and displayed if the station are sole or a shifting bottleneck i.e. if the station alone are the systems bottleneck at a specific time or if it together with another station are the bottleneck. The method is further described in chapter *2.4.1 Bottleneck detection methods.* The results of the shifting bottleneck analysis are displayed in figure 29 and figure 30 below.

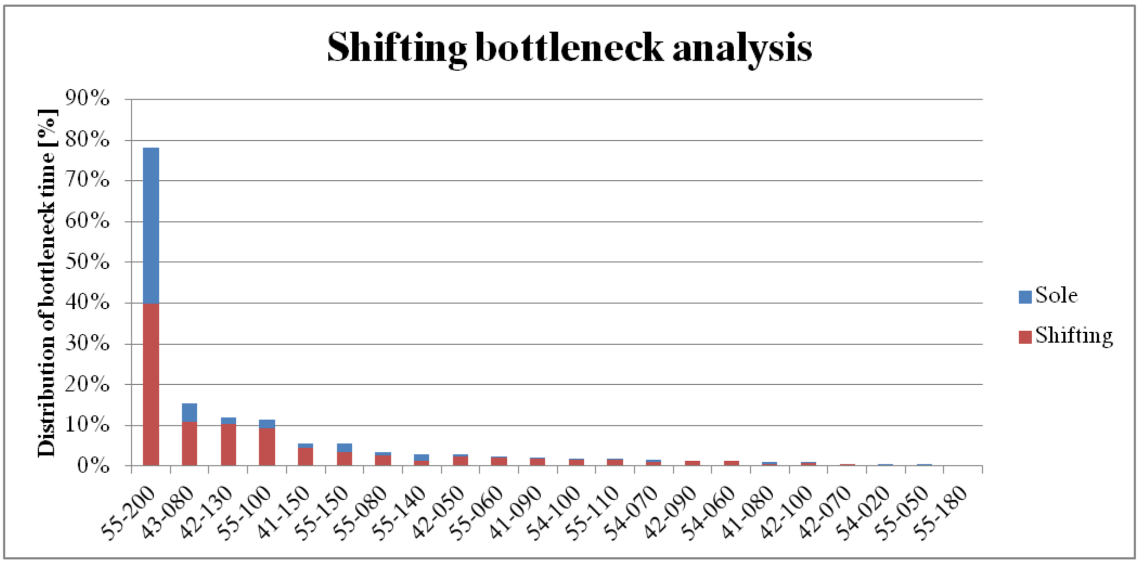

Figure 29, Results from the shifting bottleneck analysis.

As seen in figure 29 station 55-200, which is located at the very end of module six, is dominant as the systems bottleneck, both as a sole bottleneck and as shifting. Over the time period of 24 hours station 55-200 was a sole bottleneck 53% of the time and a shifting bottleneck 23% of the time. This makes station 55-200 to the primary bottleneck and the other stations, enlarged in figure 30, to secondary bottlenecks.

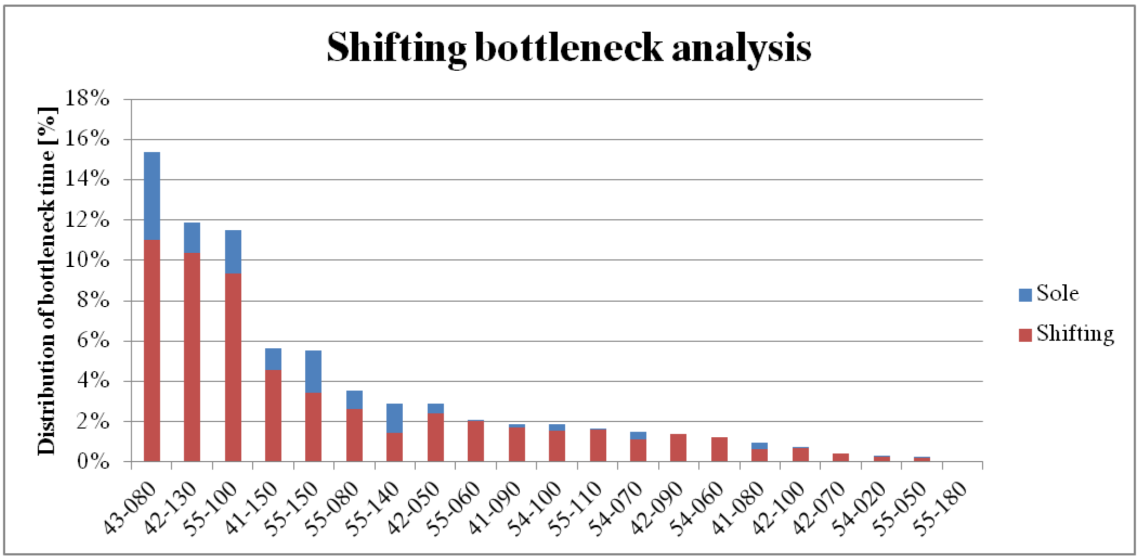

Figure 30, the systems secondary bottlenecks.

The fact that the bottlenecks could be categorized into primary, secondary and non-bottlenecks are one of the main advantages with the shifting bottle neck method, something that not could be done using the utilisation method. According to Roser et al. (2002) improving secondary bottlenecks will increase the throughput of the system since the primary bottleneck' idle time will decrease. However, it is important to solve the primary bottleneck before moving on with any of the secondary bottlenecks, since the system otherwise still is limited by the primary bottleneck. It is also is important to always do a new bottleneck analysis when changes have been applied in the system. For example, station 43-080, 42-130 and 55-100 are the top three secondary bottlenecks for the system at this moment, however one of them do not necessarily need to be the new primary bottleneck when 55-200 have been removed.

The pallets are not included in the shifting bottleneck analysis since they do not have the same conditions as the stations. The pallets move through the flow of stations and behave more as products than stations. Therefore, the shifting bottleneck method was complemented with an utilisation bottleneck analysis. This analysis was performed by calculating the average utilisation, working + disruption, for each station and the three different pallets. The calculations were based on 40 days of production, with 5 days removed warm-up period. Further description of the method could be found in chapter *2.4.1 Bottleneck detection methods.* The results are visualized in figure 31 and an enlargement of the top 20 utilisation is illustrated in figure 32.

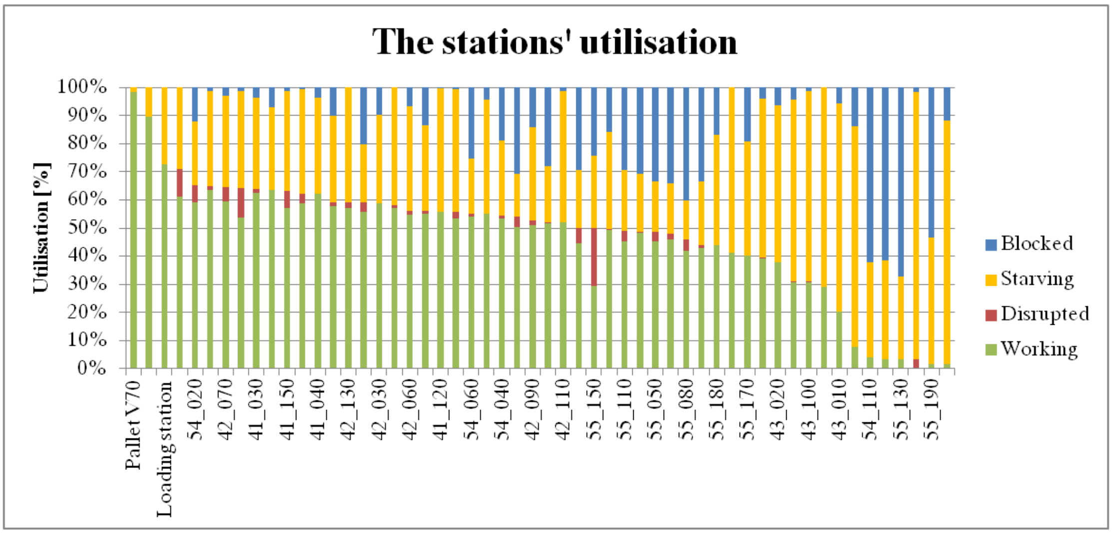

Figure 31, utilisation bottleneck analysis of stations and pallets.

The diagram has been sorted from highest to lowest utilisation, were green represent working stage and red disruptions. The stages starved and blocked are represented in yellow and blue. As seen are all stations starved and to some degree also blocked which results in that the main part of all stations have lower than 70 percent utilisation. This could be explained by looking at the pallets utilisation, according to Roser et al. (2002) are the one with the highest utilisation the systems bottleneck. According to the definition are the V70 pallet the systems bottleneck with an utilisation at 98,5 percentage, followed by pallet S60V60 with an utilisation at 89,4 percentage, illustrated in figure 32 below.

Notable are that pallet S80 and only have a utilisation of 41,2 percentage and is therefore not among the top stations below in figure 32. This could be explained by the low number of S80 pallets and the limitations for the system it results in. As explained above in the section 5.9.1 *Description of the finished simulation model* of the fabrics 81 pallets consists 28 of V70 pallets and 47 of S60V60 pallets, which leaves only six remaining pallets for the model S80. However, those six is more than enough, in reality are only three S80 pallets needed, for the product mix considered, but with today's logic six pallets needs to be dedicated to the S80 due to the large amount of time spent in the return flow for empty pallets.

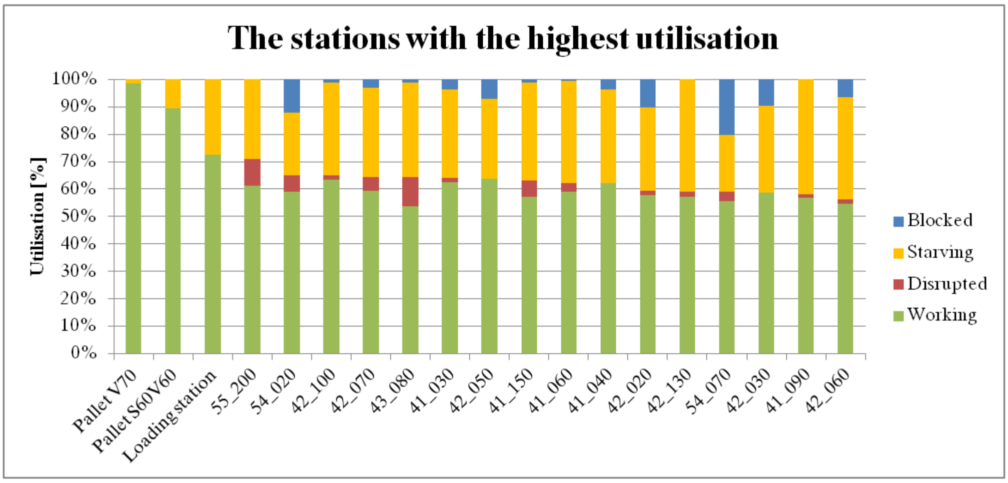

Figure 32, top 20 stations and pallets according to utilisation.

That the pallets are one of the systems bottleneck's are also displayed by the fact that the loading station, 11-73-680, are starved to 27 percent even though one of the assumption in the simulation model were that there always were products to load on the pallets. This result are in accordance to the static analysis that showed that station 11-73-680 often were starved, see figure 17, even though the large under body buffer before 11-73-680 as good as never is empty.

Since the system's first station only has an utilisation of 73 percent, even though it always has access to products, it is no wonder that the rest of the system have an even lower utilisation rate. After the pallets are 55-200 the station with the highest utilisation, which influence as a system constraint already have been investigated in the shifting bottleneck analysis and visualized in figure 29. The two performed bottleneck analysis also displays what Roser et al. (2002) did conclude in their article, see section 2.4.1. Bottleneck detection methods, that even though a number of connected stations have equally large utilisation they could be proven to have differently affects as constraints in the system. One example of this is station 54-020 that has the second largest utilisation grade of all stations but has a very small influence as the systems constraint according to the shifting bottleneck analysis, see figure 30.

According to Roser et al. (2002) the earlier a bottleneck are located in a series of connected stations the larger influence it has on the later stations starvation grade. Due to this reason it is remarkable that station 55-200 has such a large influence as the systems constraint despite the fact that it is the last station in the system. Unfortunately the pallets could not be included in the shifting bottleneck analysis but it is probable that they have a large influence on constraining the system, since they both have the highest utilisation grade and affect the system input. The influence of the pallets therefore has to be examined by conductive experiments in the simulation model, in order to determine which constraint that is the primary bottleneck.

6.2.4 Experimental phase

The experiments were constructed in order to confirm or reject the suspected bottlenecks found in the bottleneck analysis in the section *Bottleneck detection* above. They were also in accordance to the performed static analysis, see section *5.8 Static analysis of module five and six.* The full list of performed experiments is represented below and further discussed later in this section.

- Manage the production based on the flow of pallets
- Investigate station 55-200's influence on the system
- Examine the influence of station 43-080
- Investigate station 54-020's influence at the system
- Inspect so that the built in simplification of line 51-57 and 52-56 do not have a negative influence on the model's validation.

No more than two experiments were combined, since the more combinations the simulation model consists of the further away it stands in relation to the real production and the validity of the results are compromised. Below are the results for each experiment presented and analysed.

Managing the production based on the flow of pallets

In order to investigate the influence of the pallets availability on the system two experiments to increase the pallets utilisation were constructed. Both experiments aimed at avoid starving the loading station 11-73-680 when pallets were accessible, the first by loading the products on the first available pallet and the second by making it possible for the loading station to match the ten upcoming orders to available pallets.

The first experiment was designed to base the product input on the flow of pallets. Since the numbers of the three different pallets are designed to fit the mix of products the right mix of pallets should result in the right outcome of products. Therefore, an experiment were constructed were the right product were loaded on the first available pallet. However, a conclusion was soon drawn that it was too complex to assure that the right outcome was created since the mix of pallets is never perfect. In order for this experiment to work the product mix have to be able to translate into whole pallets, since pallets can't split up in halves and quarters. This was a non-realistic requirement since the product mix is based on customer orders, which almost always lead to uneven percentages. There would always be a slight rounding off on the percentages which would displace the product mix of the output.

The second experiment was designed to make it possible for the loading station to match the ten upcoming orders to available pallets. This experiment made it easier to assure the right outcome of the system. One advantage with the experiment is that the limitation in minimum number of pallets is removed, discussed in section *5.9.2 Description of simulation model,* which results in that a more perfect mix of pallets could be used. The more perfect mix of pallets and the fact that the pallets do not have to wait in the buffer for the right pallet to arrive to the loading station should result in a lowered starvation of the loading station, see figure 33 (highest utilisation) in section *5.9.3 Bottleneck detection,* and a higher utilisation of the pallets.

Furthermore, if the pallets do not have to wait in the pallet buffer it is no risk that the buffer becomes filled so that empty pallets have to enter the flow. One of the main advantages with this experiment is that the input becomes more even, since the waiting for the loading station, 11-73-680, is held at a minimum. Therefore, a system that behaves more like a continuous flow is accomplished. The results of the experiments showed that the pallets utilisation is heavily increased as illustrated in figure 33.

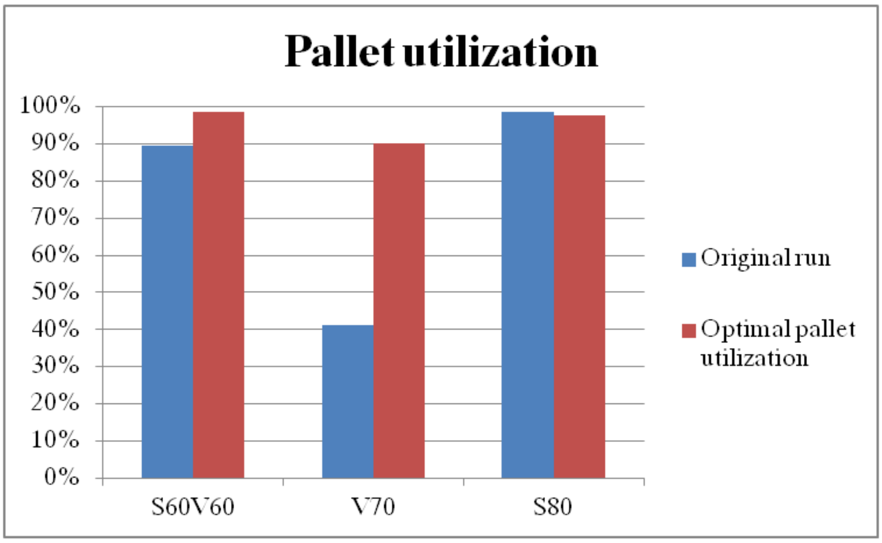

Figure 33, utilisation of pallets for the original run and the experiment.

However, despite the increased pallet utilisation and the more even flow the experiment did not show an increased throughput in jobs per hour. In order to ensure this result an additional experiment was performed with an increased number of pallets. This experiment also did not increase the output of the production system. Hence, the pallets are a secondary bottleneck and further experiments need to be performed in order to locate the primary bottleneck.

Station 55-200's influence on the system capacity

Initially two experiments were constructed to evaluate station 55-200's influence on the system capacity: one where the station was redefined with a lower cycle time than reality, from close to 60 seconds to 50 seconds, and one experiment when the stations availability was elevated from 95% to 98%. These two experiments were made in order to see what station 55-200's main problem was, too high cycle time or too low availability. After separate experiments have been performed a combination of them were performed in order to see how 55-200 influenced the system in an optimized mode. In figure 34 below the resulting JPH from the different experiments are displayed.

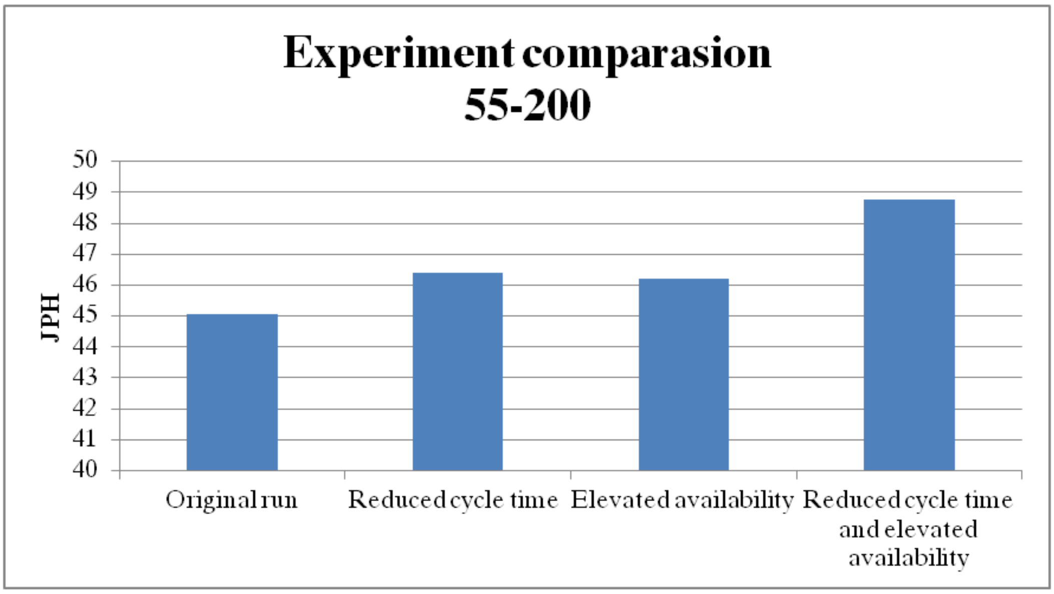

Figure 34, comparison of experiments with station 55-200 and pallet optimisation.

As the blue bars in figure 34 clearly state, all three experiments on station 55-200 resulted in a higher JPH. In the original run the factory reached 45,0 JPH, but with the above described changes to station 55-200 a JPH of 48,8 car bodies can be reached. The graph displays that VCT rather should focus on lowering station 55-200's cycle time than try to increase the availability of the station since lowered cycle time yielded in a larger production capacity than the increased availability. However, in order to reduce the cycle time VCT need most probably to rebuild the station, which hopefully also leads to increased availability.

Station 43-080's influence on the system capacity

To examine station 43-080's influence on the system capacity an experiment was performed where the stations availability was elevated from 95% to 98%. An experiment with the cycle times was not relevant since the station already has a very low cycle time compared to the rest of the stations in the system. The experiment resulted in no elevation in JPH, as the experiment with the pallets. Most likely because 43-080 is not the primary bottleneck.

Influence of station 54-020 on the system

Since a wide spread opinion at VCT is that the framing station 54-020 is the system's main bottleneck an experiment was performed to see the influence of 54-020 on the system. The experiment was constructed so that 54-020 received an increased availability, from 95 to 98 percent since the main problem with this station is the low availability and not high cycle time. The results yielded much like the almost identical experiment on station 43-080 in no increase of JPH and also indicates that 54-020 not is the primary bottleneck.

Effects of the simplifications for module three and four

Since module three and four, see section *5.4 Modularisation of the production system,* are heavily simplified in the model the impact of these modules on the system needed to be investigated. An experiment were therefore constructed which tested what output was achieved when the system were not limited by these modules. The results showed that the throughput only increased with 0,2 JPH when the system always had input from module three and four. This logic is unrealistic to implement in the real factory since it today is impossible to have 100 percent availability on all stations within these modules. However, it proves that the prioritization of the modules was correctly done and that the level of detail does not need to be improved on these modules in the simulation model.

6.2.5 Comparison and combinations of experiments

In this section all performed experiments are summarized and the results are visualized in table 2 below. Some experiments have also been combined and further evaluated, as seen in figure 35. However, the experiment evaluating the simplification for module three in four are not further investigated in this section since it only was an experimental validation of the model.

Experiment	Original run	Optimal pallet utilization	Reduced cycle time 55-200	Elevated availability 55-200	Elevated availability 43-080	Elevated availability 54-020
Throughput	45,06	45,05	46,41	46,19	45,04	45,07
Standard deviation	0,20	0,64	0,28	0,22	0,21	0,21

Table 2, summarized results from the experiments.

Primarily it is notable that neither the elevated availability on station 43-080 and 54-020 nor the implementation of optimal pallet utilisation resulted in a higher throughput in JPH. This shows that none of these stations or the pallets are the primary bottleneck. By considering the flow of pallets conclusion can be drawn that the primary bottleneck, station 55-200, most of the time has a queue of pallets before itself, even though the input in the system is not stable. This could be explained by the fact that station 55-200 is the last station of the system and therefore is less affected by the uneven input.

In order to investigate which of the identified three secondary bottlenecks that had the largest effect on the system combinations of these three and station 55-200 have been performed. The result of these experiments is displayed in figure 35 below.

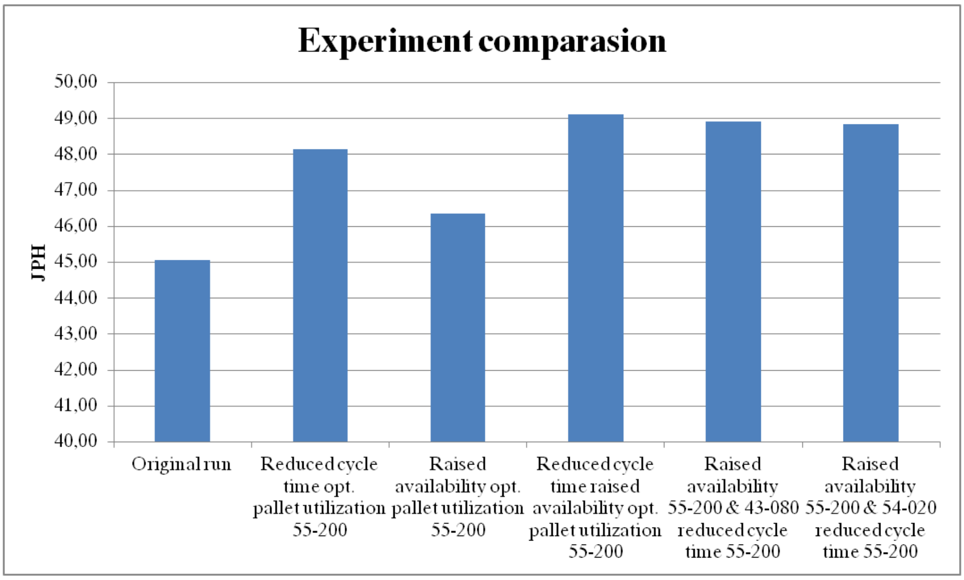

Figure 35, combination of experiments.

It is notable that the experiment with the reduced cycle times of 55-200 yields in a rather large difference in output when it is combined with the pallet utilisation experiment, from 46,6 JPH to 48,2 JPH. When this experiment combination is related to the experiment with elevated availability it became clear that the elevated availability does not profit as much from being combined with the pallet utilisation example, from 46,2 JPH to 46,4 JPH.

A conclusion could be drawn that the system has more to gain to implement the pallet logic when a cycle time have been reduced than when the availability of a station have been improved. This could be explained by the fact that the production stoppages only influence certain time intervals whilst lowered cycle times influence the system and every product continuously. Since the experiment with optimal utilisation enables the pallets to circulate more unimpededly in the system they enlarge the experiment that affect every pallet to a higher degree than the experiment that only affects some pallets.

The experiments performed on station 54-020 and station 43-080 did not raise the output, which, as stated above, indicates that they are secondary bottlenecks. Since all non-combined experiments, except for the 55-200 experiment, did not result in any change of throughput an investigation of what the primary constraint, station 55-200, limits the production system to was carried out. This was performed by investigating what maximum capacity station 55-200 could reach as an independent station, this can be demonstrated by an easy calculation explained below.

Station 55-200 has an availability of 95%, which means what five percent of the car bodies exceed their cycle time with approximately the stations MDT which is 262 seconds. 55-200 has an weighted cycle time at 57,9 seconds, however since it is an unloading station it has more or less the same cycle time for every car model. The rough estimations of the max throughput of 55-200 in JPH are calculated below.

$$57{,}9 \times 1 + 262 \times 0{,}05 = 71\ seconds/body$$

$$\frac{3600}{71} = 50{,}7\ JPH$$

This calculation shows the max throughput from 55-200 are one body every 71 seconds i.e. 50,7 JPH when it is not affected by any other limitation in the system. Therefore, even though any other station, or in fact all other stations, in the flow are optimized the max output of the system is still approximately 50,7 JPH. This since 55-200 is the last station and the main constraint in the system; i.e. the one that set the pace of the system's output.

In the thesis the limitation of the system was already set at approximately 45 JPH, which could be explained by the fact that 55-200 sometimes suffers from starvation and blockings, see figure 25. Therefore, station 55-200 is not always the only bottleneck of the system, as described with the shifting bottleneck analysis, see figure 29, thus the throughput is lowered below 50,7 JPH.

7. DISCUSSION

The project was successful in locating a primary constraint in the production system, much due to the persistence in keeping a holistic view in the search for the severest production constraint. Station 55-200 was identified as the primary bottleneck, and experiments showed that improvements of other resources did not increase the production output beyond the primary constraint. This is in accordance with theory which states that improving a secondary constraint cannot overcome the limitations of a primary constraint (Goldratt and Cox, 2004). Comparing the influence of the pallet flow with the influence of suspected bottleneck stations was not easy using bottleneck detection methods, but simulations experiments were successful in pointing out the optimal solution as a combination of improvements on station 55-200 as well as improvements on the pallet utilisation.

The major uncertainty in the thesis has been the large amount of data. The data have been difficult to collect, many systems and databases have been involved which none have been particularly user-friendly when it comes to collecting large amounts of data. The databases are also custom made at different times, by different people and for different purposes, which makes it very hard to know how the data have been collected. Therefore it is also difficult to verify the accuracy of the data. Even if data is validated in for example one station, it is impossible to know if the other stations' data is correct due to the lack of standardization in the data collection all the way down to the configuration of the PLCs. Since the databases are not interconnected the data needs not only to be collected, it needs to be reworked, which is very time-consuming. For example uptime and availability are not recorded automatically and therefore need to be calculated using downtime.

Both the static analyses and the simulation model are founded on the collected data and their input must be questioned. The first bottleneck detection analyses, displayed in figure 17 and figure 25, seem to point out a constraint in the beginning of module six, or module five. This is confusing considering that the static analysis performed on the cycle times and the inherent disturbances pointed out 55-200, the very last station in module six, as a potential bottleneck. It could be that the modified bottleneck detection method used in the static analyses has the same limitations, or even more severe limitations than, the common waiting time method presented in section *2.4.1 Bottleneck detection methods.* All buffers do not have unlimited capacity and the queues do not behave as queues in other production systems due to the complexity introduced when using a limited number of pallets for the different product types.

The results of the shifting bottleneck detection performed using the simulation do however find that station 55-200 is a bottleneck, and so does the utilisation method. The utilisation method is in this case a too rough estimation since many stations reach the same utilisation. Furthermore, according to Roser et al. (2003) the utilisation method does not take into consideration that a station early in the production flow has a higher potential of becoming a bottleneck when similar stations are located after each other. The utilisation method is however a very fast method and it could also be performed on the pallets. Initially the shifting bottleneck method was planned to include the pallet flow, however large difficulties were met when trying to define the active and inactive states for the pallets. The pallets behave more like the products in the flow than the stations, which makes it hard to set a definition that is fair to both parties in a comparison. Experiments therefore needed to be constructed in order to evaluate whether the pallets are the primary bottleneck or not, which they were concluded not to be.

What always needs to be considered in projects like this are the assumptions made. One early assumption in the project was that around 30-40 days of historical data were enough to draw conclusions. This assumption was made due to the fact that there was no more history saved in the databases. This assumption have been checked later on, since the project have been carried out during approximately 20 weeks, and more data have become available as time passed. No drastical changes have occurred during this time, except for the roof beam station 54-010 which was improved after the static analysis have been carried out. It can only be speculated how the prioritisation would have looked during another time period, but station 54-010 would probably not have been such a high priority today. Before the simulated experiments were constructed this change had been discovered and the new improved station 54-010 was inserted into the model, thus the experiments are valid to the production of today.

Perhaps module three and four, the left and right body sides, would have been prioritised, but an experiment have however proven that those modules are not the primary bottlenecks nor have large influence on the system, see section *5.9.4 Experimental phase.* Therefore, the simplification regarding module three and four in the simulation model seems to be a valid assumption. They need however to be considered when the first bottleneck have been reduced or removed, since the new primary constraint very well could move into module three or four. Bottleneck detection is always an iterative work task, and the largest bottleneck need to be re-identified after the previous ones has been removed, see section *2.4 Theory of constraints.*

The most general simplification in the simulation model is that the under body buffer can always deliver products and that the K10 buffer can always receive products. According to figure 1 on page 1 it does however seem like this assumption is not far from the truth, the question is when the assumption is not valid anymore. How large an increase in capacity the surrounding systems can handle is not evaluated, but a couple of car bodies per hour should not pose a problem, considering figure 1 on page 1. Research have to be made on the preceding and subsequent production if large capacity changes occur, in order to assure that they can handle the increase in capacity, otherwise the bottleneck will shift into one of the areas beyond the buffers that delimit the thesis focus. The buffers, displayed in figure 1 on page 1, could work as an indication that this has happened.

Another interesting simplification is that break times, maintenance stoppages and nights have not been included in the simulation model. A relevant question is how this affects the model. It did become easier to verify the model without the mentioned stoppages, and it also eased the experiment constructions since it is easier to evaluate a steady state model. If the production stoppages were to be introduced into the simulation model it is not given that the experiments would have been constructed the way they were in the thesis. The static analysis also have imperfections due to the break times, since the automatic stations continue whilst the manual ones stand still, creating queues in front of the manual station and emptying the line after it. Break times can however not be considered an unnecessary bottleneck, but their influence could be decreased by for example assuring that enough buffer capacity is available for the station to continue whilst the worker takes a break. The break times have not been evaluated in the thesis. Surely the break times influence the production output, but due to union related reasons and the fact that breaks are necessary the social sustainability has to be considered. The influence breaks have on the production output cannot simply be reduced or removed without comprehensive investigations and reorganisation.

Extreme queues, or tail formations, are unfortunately the opposite of the desired continuous flow. Since the pallets are very expensive it is not an option to fill the production with pallets until there are enough pallets to keep every station occupied. This means that to strive for a continuous flow the pallets should at least be as utilised as possible, i.e. not wait in queue to receive a product but instead be active in the production flow. The problem with tail formation is extra problematic in combination with classic bottleneck stations, since the tail formations are preceded and followed by an empty production flow, which results in unutilised machines. When a bottleneck is unutilised it is extremely unfortunate for the entire production system. Since the pallets constrain the system from the very beginning; the modified waiting time method used in section *5.5.3 Production disturbances* and section *5.8.3 Production disturbances in module five and six* will always show a large extent of starvation since the stations are waiting for pallets.

Moving on, the results were very interesting when the combination of cycle time reduction and optimal pallet utilisation was examined. This combination both strives for a more continuous flow with the pallet experiment, and the limit is elevated by 55-200 – resulting in a very beneficial combination which radically increases the system capacity.

A surprising result was also the appearance of line 41, 42 and 43 among the top bottleneck in the shifting bottleneck analysis. The mentioned production lines were all written off during the static analysis since no data indicated that any of the mentioned lines could pose a constraint in the system. The shifting bottleneck analysis has the great advantage of showing that a station early in the flow is more likely to be a system constraint, which probably is the reason that line 41, 42 and 43 appears in the results, they are so early that the slightest constraint becomes serious.

No economic aspects have been taken into consideration when constructing the experiments, i.e. the improvements may be too expensive to implement. It would have been very interesting to compare the bottlenecks with regard to regard to the cost of reducing or removing them. This was however not possible within the given time frame of the project.

8. CONCLUSION AND RECOMMENDATIONS

This chapter presents the conclusions and future recommendations that were raised through the thesis. The research questions of the thesis, formulated in section *1.3 Problem formulation,* are repeated below in order to evaluate to what degree they have been fulfilled.

RQ1 Which factors contribute to the system losses in the body shop?
RQ2 How much do the contributing factors affect the throughput in the delimited area of the body shop?

Two main factors were found to contribute to the system losses, mainly different bottlenecks and also the complexity of the system. A bottleneck which limits the capacity constrains the entire system and can alone be responsible for a great deal of the system losses. Station 55-200 were found to be the primary bottleneck, thus the focus should be to improve this station, preferably by lowering the cycle time. By also implementing the proposed approach for pallet control, a synergy could be achieved resulting in an even greater increase of the output by up to 9%. A more efficient production could reduce the need to work overtime such as night shifts and weekend shifts.

A recommendation for Volvo cars Torslanda, VCT, is to implement a more systematic approach for bottleneck detection and production development. As Goldratt and Cox (2004) point out: “An hour saved at a non-bottleneck is a mirage”. An iterative plan for reduction or removing of bottlenecks is necessary, and could with great advantage be carried out using the invaluable tool of flow simulation, since the production system at VCT is very complex and difficult to grasp in its entirety.

Another recommendation which would ease the production developers’ work is for them to work closer together with the database developers. Assuring from the beginning that the data used for analyses are collected in a satisfying and standardized way would save a tremendous amount of time, and of course also improve the analyses. To avoid misunderstandings all data systems which are not properly updated should be closed down or at least marked clearly that they are out of date.

The second factor that contributed to the system losses was found to be the complexity of the system. Constraints in the system have been built in by using a limited number of pallets. Therefore, the stations will always starve to some extent. The system is also extra sensitive due to the merging of four flows into one at the framing station, which however was proven not to be the bottleneck in VCT’s production today.

A final recommendation for VCT is to put the resulting simulation model in use when this project is finished. However, depending on the purpose of the future study the model might have to be complemented. Using the model is especially beneficial when evaluating the needed pallet mix for different product mixes, since it saves valuable time and enables what-if analyses. It is much less costly to search for an optimal solution in the model rather than in the real factory.

9. REFERENCES

Banks J. (1998) *Handbook of Simulation - Principles, Methodology, Advances, Applications, and Practice.* Hoboken: Wiley & Sons.

Banks, J. (2010) *Discrete-event system simulation.* Fifth Edition. New Jersey: Pearson Education.

Banks J. & Carson S J. (1986) Introduction to Discrete-Event Simulation. In *WSC '86 Proceedings of the 18th conference on Winter simulation.* 8-10 December 1986, Washington, D.C. p. 17-23.

Carson II, S. J. (2005) Introduction to modeling and Simulation. *Proceedings of the 2005 Winter Simulation Conference*. 4-7 December 2005, Orlando FL, p. 16-23.

Conger S. (2011) *Process Mapping and Management.* New York: Business Expert Press, LLC.

Damelio, R. (1996) *Basics of Process Mapping.* Portland: Productivity Press.

Damelio, R. (2011) *Basics of Process Mapping, 2nd edition*. New-York: CRC Press.

Dickens, M. (2007) *Process Mapping*. Oak Brook: Reed Business Information, a division of Reed Elsevier, Inc.

Djassemi, M. and Olsen, O E. (2010) The Impact of Lean Level Material Flow on Performance of Manufacturing Systems for Large Complex Parts. *Production and Inventory Management Journal, vol. 46, no. 1, pp. 27-35.*

Gardiner C S., Blackstone H J., Gardiner R L. (1993) Drum-Bubber-Rope and Buffer Management: Impact on Production Management Study and Practices. *International Journal of Operations & Productions Management*, Vol.13, No. 6, pp. 68-78.

Goldratt M E. & Cox J. (2004) *The Goal: A Process of Ongoing Improvement, 3^{rd} revised Edition.* Aldershot : Gower.

Grassmann, K W. (2008) Warmup periods in simulation can be detrimental. *Probability in the Engineering and Informational Sciences,* Vol. 22, No. 03, pp. 415-429.

Jina J., Bhattacharya K A., Walton D A. (1997) Applying lean principles for high product variety and low volumes, some issues and propositions. *Logistics Information Management*, vol. 10, nr. 1, ss. 5-13.

Lawrence R S. and Buss H A. (1995) Economic analysis of production bottlenecks. *Mathematical Problems in Engineering*, vol. 1, no. 4, pp. 341-363.

Lima, E., Chwif, L., Barreto, M. (2008) Methodology for selecting the best suitable bottleneck detection method. In *2008 Winter Simulation Conference*; 7-10 December 2008, Miami, FL. p. 1746-1751.

Liker K J. (2004) The Toyota Way: fourteen management principles from the world's greatest manufacturer. New York: McGraw-Hill.

Linton, J. (2007) Process Mapping and Design. San Francisco: UP Media Group, Inc.

Rahman, S. (1998) Theory of Constraints – A review of the philosophy and its applications. *International Journal of Operations & Productions Management*, Vol.18, No. 4, pp. 336-355.

Robinson, S. Brooks, R. Kotiadis, K. Van Der Zee, D. (2010) *Conceptual Modeling for Discrete-Event Simulation.* New-York: CRC Press.

Roser, C., Nakano M. and Tanaka M. (2003) Comparison of bottleneck detection methods for AGV systems. In *2003 Winter Simulation Conference*; 7-10 December 2003, New Orleans, LA. p. 1192-1198.

Roser, C., Nakano M. and Tanaka M. (2002) Shifting Bottleneck Detection. In *2002 Winter Simulation Conference*; 8-11 December 2002, San Diego, CA. p. 1079-1086.

Rother, M. & Shook, J. (2003) *Learning to see: value-stream mapping to create value and eliminate muda.* Cambridge, Massachusetts: The Lean Enterprise Institute Inc.

Sargent, G R. (1984) Simulation Model Validation. *Simulation and Model-Based Methodologies:*
An Integrative View. New York: Springer-Verlag Berlin Heidelberg.

Shannon, E R. (1998) *Introduction to the Art and Science of Simulation*. Los Alamitos, USA: IEEE Computer Society Press.

Siemens Industry Software AB. (2013) Plant Simulation. *Plant Simulation: PLM lösningar från Siemens PLM Software – Sverige.*
http://www.plm.automation.siemens.com/se_se/products/
tecnomatix/plant_design/plant_simulation.shtml (2013-05-10)

Tapping D., Luyster T., Schuker T. (2002) V*alue Stream Management: Eight Steps to Planning, Mapping, and Sustaining Lean Improvements.* New York: Productivity Press.

Plenert G. (2007) *Reinventing Lean.* Burlington: Buttersworth-Heinemann.

APPENDIX A

Interview questionnaire

In your experience, are there any problems with the body shop? Describe them.

What reasons can you see for why the body shop cannot reach its theoretical capacity?

Are there any areas of the body shop that are extra sensitive and pose high risk?

In your experience, are there any bottlenecks in module six?

Based on the module map, which module would you say poses the highest risk in constraining the system?

Do you see any problems with the lack of product sequencing in the body shop? Why/Why not?

In your experience, are there any problems with the pallet flow? What problems? Why?

There are many buffers in the system, mainly due to the many long transportations, do you consider this a problem? Why? Why not?

Based on graphs from the static analysis:

The first station after the under body buffer seems to starve relatively often, why is that?

Is it correct that the two body side flows affect the system unequally?

Module five seems to have a rather low output, why? Do the break times have an influence?

In your opinion, why does module six have such low output?