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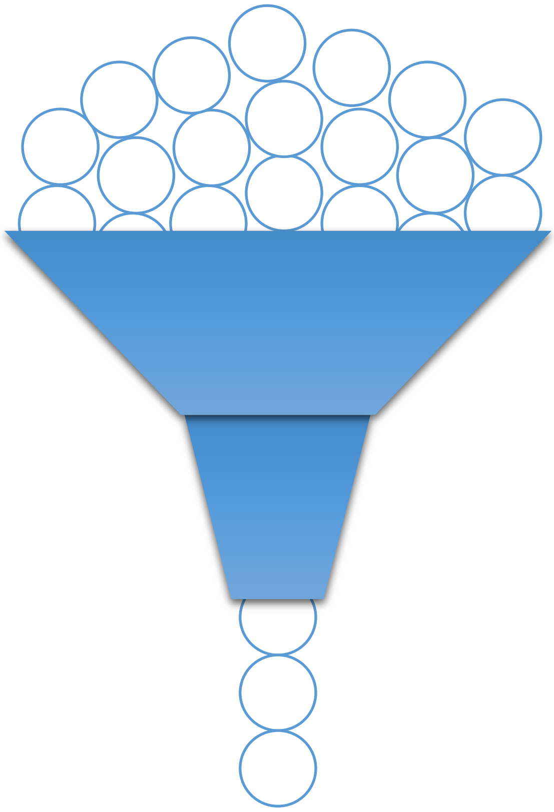

Bottleneck detection in manufacturing

A throughput case study at SCANIA CV

Master's thesis in Production engineering

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Through KPIs

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1 Abstract

Manufacturing industry today is becoming increasingly competitive and to stay in business organisations must constantly improve their productivity. To get most of the improvements they should be targeted where they benefit the most, also called the bottlenecks of the system. The bottlenecks are what limits the throughput of the system the most, and to increase the throughput one must improve the bottlenecks. A systematic approach for finding and working with the bottlenecks is therefore important. It is only by improving the bottleneck a real improvement in throughput can be achieved as all other improvements only leads to more waiting time. As a part of this focus on productivity the companies are measuring more parameters of the organization than ever before. These are commonly referred to as key performance indicators or KPIs.

The purpose of this thesis is to help organisations improve their productivity. It aims at increasing the knowledge of what a bottleneck is, why a resource becomes a bottleneck in a manufacturing line and how bottlenecks effectively should be managed. This are to be examined by a case study at the Swedish heavy vehicle manufacturer Scania CV. By doing so, the goal is to find out the relationship between a machines KPIs and its likeliness of being a bottleneck.

As a first step, the available data is cleaned and analysed with respect of finding the bottleneck for given timeframes as well as articles. Various bottleneck methods are compared with respect to their usability as well as their results. A correlation analysis is then made to find out if they correlate or that is, if one can predict the bottleneck by examining the KPIs.

Throughput bottlenecks were identified both on a real-time level and as an average for a period of time using several methods such as average active period, shifting bottleneck and ITV method. The results show that the methods often fail to point out the same bottleneck. There is also no clear correlation among a machines KPIs and its likeliness to be a bottleneck of the system. It also shows that the bottleneck shifts during batches due to disruptions in the machines, meaning that the slowest machine is indeed not necessarily the bottleneck.

Keywords: Bottleneck, Production, Manufacturing, KPI, Correlation

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I would also like to thank my industrial supervisor at the case company Scania CV, Ulf Bjarre for his support and helpful feedback along the way as well as giving me the opportunity to do this thesis in the first place. It has been quite a journey since you first hired me for my first internship four years ago and I look very much forward to working with you for many years to come. As I have spent most of the time working with the thesis at the office, I have mainly my colleagues to thank for giving me a pleasant time and keeping me company. It have been a genuine pleasure getting to know you guys!

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Axel Ericson
Gothenburg, May 2017

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3 Introduction

In this chapter, an introduction to the thesis is presented. The aim is to give the reader an understanding to the significance of the study as well as an understanding of what the aim and goal is.

3.1 Background

Industry today is becoming increasingly competitive. There is a hard competition from domestic firms, and the exchange of products and services around the globe means that companies in Sweden also have to compete with low wage countries. First from Asia, and after the Berlin Wall in 1989 the easily accessible countries in Eastern Europe as well (Hedman, 2016). To stay competitive, the western industry has to be a lot more effective and thus yield a higher productivity per man hour spent. It is therefore of great importance not only for the individual companies but also for the economic sustainability for the country as a whole.

The good news is that there is indeed a large improvement potential in the Swedish manufacturing industry. Hedman (2016) points out that the average overall equipment efficiency (OEE) in Swedish industry is only a mere 65%. Peter Almström and Anders Kinnander (2008) came previously with the same conclusions with their extensive productivity potential assessments. Other studies investigating the use of OEE for maintenance improvements showed even lower utilization with an average OEE of only 51,4 among the Swedish companies (Ylipää et al., 2016). The trend has been the same since the late 20-th century, as Jacobs et al (1997) proved when they showed that the industry was only using half of its capacity. The question is then how to find and exploit this hidden potential.

One of the main parameters by which the performance of a production system is evaluated is by its throughput, or the number of parts it produces during a given period. This thesis aims at finding out how the throughput can be increased without increasing the expenses. It turns out that an improvement in one machine does not have to make an improvement of the overall throughput of the plant, as indicated by Goldratt and Cox in their book “the Goal” (1993). Improvements must be made on the bottleneck of the system since every second won in a non-bottleneck only adds to the time the machine spends waiting for the bottleneck. In a production environment, the bottleneck is said to be the resource that is the most limiting to the overall system performance. This could for instance be because it is the slowest operating machine or the one with the most disturbances.

To improve the bottleneck resource, one must first find it. This have previously been a long and difficult process that involves analytics or simulation (Leporis and Králová, 2010). As a production process of its nature is very varying, the bottleneck can shift due to for instance a change of cycle times or disruptions in the process from day to day and even hour to hour. Therefore, a lot of research during the last years have been about automatically finding the bottleneck for instance by analysing data from the IT-systems controlling the process. By doing so, the bottlenecks could easily be found in real-time which allows for continuous adjustments for and improvements of the process.

For daily operations management, most companies use key performance indicators (KPIs). This is figures that are related either to performance of the organization such as profit, or performance of a part of the organization such as average production per unit of time for a machine or line on the shop floor. The idea is that they should reflect the performance and thus show if the company is improving as well as allowing benchmarking to similar organizations.

3.2 Purpose

The purpose of this thesis is to show how the productivity of a production system can be increased. This should be done by increasing the knowledge about bottlenecks and thus creating an efficient management system for handling bottlenecks in the production. By doing so, the companies can stay competitive and thus contributing to the economical sustainability of the country. A more effective use of the resources will also help reducing the environmental impact as more can be produced without building new plants.

3.3 Aim

The thesis aims at creating a deeper understanding about bottlenecks and why a resource becomes a bottleneck, how they should be managed and why this is important. In the thesis, various methods for finding the bottleneck is used which will contribute to a deeper understanding of the applicability as well as accuracy of different methods for different cases.

It also aims at investigating the correlation between the key performance indicators of a machine and its likeliness of being a bottleneck. By connecting the bottlenecks to the KPIs it should be easy to see the actual effect of bottleneck not only on throughput but also on the bottom line, as well as targeting the improvements at the bottleneck where they will yield the most return.

3.4 Research questions

Q1: What are the main reasons that a machine in an automatic serial manufacturing line becomes a bottleneck?

Q2: What is the relation between the machines likeliness of being the BN and its KPIs?

3.5 Delimitations

- Only data from the selected lines at the one company industrial case study will be used.
- The data for the analysis will be acquired from the manufacturing execution system (MES) only and the data will be assumed to be reliable.
- Only currently available bottleneck detection methods will be used meaning that no new methods will be developed.

4 Literature review

In this chapter, the currently available knowledge about bottlenecks, KPIs and correlation analyses are presented. The aim is to give the reader a good theoretical background, as well as creating a common platform regarding definitions of the methods and figures presented throughout this paper.

4.1 Bottleneck definition

There are many reasons that a machine can be the bottleneck. Chiang et al. (1998) propose categorizing machines as being uptime bottleneck indicating that the reason is either because the machine is working to slow when it is producing or it is not available for production enough time because of disturbances.

There exist several definitions of what makes a resource a bottleneck (i.e. Betterton and Silver, 2011; Chiang et al., 1998). An early definition as proposed by Goldratt and Cox (1993) is that it is any resource with a demand greater than its capacity. Betterton and Silver (2011) states that most of the current definitions are not relating to the actual reason that a resource is a bottleneck. They do not take all parameters that can make a machine a bottleneck into account but only considers theoretical capacity and throughput. Betterton and Silver (2011) continue by suggesting yet another one:

"The bottleneck is the resource that affects the performance of a system in the strongest manner, that is, the resource that, for a given differential increment of change, has the largest influence on system performance." (Betterton and Silver, 2011).

This uses throughput as the system performance measurement (Ibid), but especially in today's competitive environment where throughput might no longer be the main measurement but delivery accuracy, just-in-time and quality is just as important this might give an insufficient answer as indicated by Chen (2008). He points out the gap between the industries KPIs and their business goals, where focusing on outdated cost management systems might prevent them from fulfilling their overall purpose of putting the customer first. Hence, they might not point out the overall bottleneck of the system and lead to sub-optimizations.

4.2 Bottleneck detection methods

During the last decades, there have been several methods in use for finding the bottleneck ranging from looking at the utilization of the resources (Hopp and Spearman, 2000) to various analytical methods examining and comparing the machines active periods. Some of them like for instance the average waiting time method are aimed solely at the manufacturing machines of the systems and does not consider operators, automated guided vehicles (AGVs) or supply and demand (Roser, et al., 2001). This could potentially be a problem as manual work with setup, loading and unloading the machine etc. is considered to be a common bottleneck within the industry (Almström, 2012).

4.2.1 Bottleneck detection procedure

There are four main ways to find the bottleneck in a system: analytically, discrete event simulation, using the data itself or by manually looking at buffer levels. Each of them has their own advantages and disadvantages as described below. Within each method, there are a number of bottleneck indications and techniques to find the bottleneck that are described in the following chapters.

The analytical method is based on mathematical calculations which gives the bottleneck (Yu and Matta, 2014), either by simply comparing capacity or including measured data from production such as starving or blocking percentages. While the answers can be satisfying it is difficult and indeed sometimes practically impossible to perform due to the complexity of the production system (Leporis and Králová, 2010).

Simulation models are another popular approach (Ibid) which has gained substantial popularity since its beginning in the early 1980s. When using this method, a digital model of the system is created and the model can then run for an arbitrary period of time. The main benefit of the simulation model is that it can give very detailed information about the production such as average queue sizes or utilization as well as statistics of failures and maintenance activities. Another benefit is that it is easy to try out new changes and see how they affect the system. The downsides is that it is indeed very time consuming to perform a simulation. Also, a model is never a true representation of the system which means that wrong assumptions or misinterpretations can yield a very different result. Besides, the model easily gets outdated as the production system is changing and keeping it up to date is expensive.

There is also an increasing interest in the data-driven bottleneck detection methods, that is analysis from the data collected from the manufacturing system (Ibid). With that, many of the drawbacks with analytical or simulation models can be avoided. Knowing the bottleneck in real-time allow the owners of the system to optimize it accordingly.

Roser et al. (2015) proposed a more practical approach called “the bottleneck walk” where one walks among the flow and look at buffer levels in real-time to determine the bottleneck. This is neither data driven nor analytical but a handy tool that can be used by the engineers or operators.

4.2.2 Lowest production rate

Ideally, it would be sufficient to look at the cycle times and thus the production rates for the machines in the system. The machine with the longest cycle time would have the lowest capacity and therefore be the bottleneck (i.e. Kuo et al. 1996; Hopp and Spearman, 2000). And indeed, this is how many in the industry are finding bottlenecks today. As for the benefits, the cycle time is usually easily found simply using a stopwatch. For numerically controlled manufacturing operations, the cycle times also tend to be consistent for each machine and a given product meaning that not all cycles have to be measured as long as no changes are made.

The problem however, lies in that very few manufacturing operations are working as intended a majority of the time. Machines break down, tools must be changed possibly within a batch, setups should be performed between articles and so forth. Random disturbances such as machine breakdowns, human errors will also interrupt the process. And due to dependencies among the operations, such an event might interrupt not only that operation but the system as a whole. Goldratt and Cox (1993) successfully proved that a well-balanced system with the same cycle times for all of the machines in reality still never would produce one part per cycle time. “The maximum deviation of a preceding operation will become the starting point of a subsequent operation” (Goldratt and Cox, 1993).

4.2.2.1 Data requirements

This method only requires the cycle times for each operation.

4.2.3 Utilization

The utilization is defined as the percentage of time the resource is not idle due to lack of work. It's defined as the time spent producing divided by the effective process time, excluding setups or breakdowns that is interrupting the process. Because of this, it is sometimes referred to as the *effective process time method.* In a serial line, the machine with the largest utilization is considered to be the bottleneck. (Betterton & Silver, 2011)

4.2.3.1 Data requirements

In order to calculate the utilization for a machine, one need the time it has produced and the total time it has been available for producing.

4.2.4 Active period method

The duration that a machine is active processing or down due to failure without interruptions is called an active period. Example of an interruptions are when the machine is idle due to it being blocked or starved by another machine (Betterton & Silver, 2011). The method can be divided into two separate methods where the machine with either the longest average active period or the highest percentage of active time is considered to be the most likely bottleneck. This is because it is the most likely to set a constraint to the other machines. In other words, it is working at a pace closest to its own maximum capacity and there is a minimum of idle capacity to use.

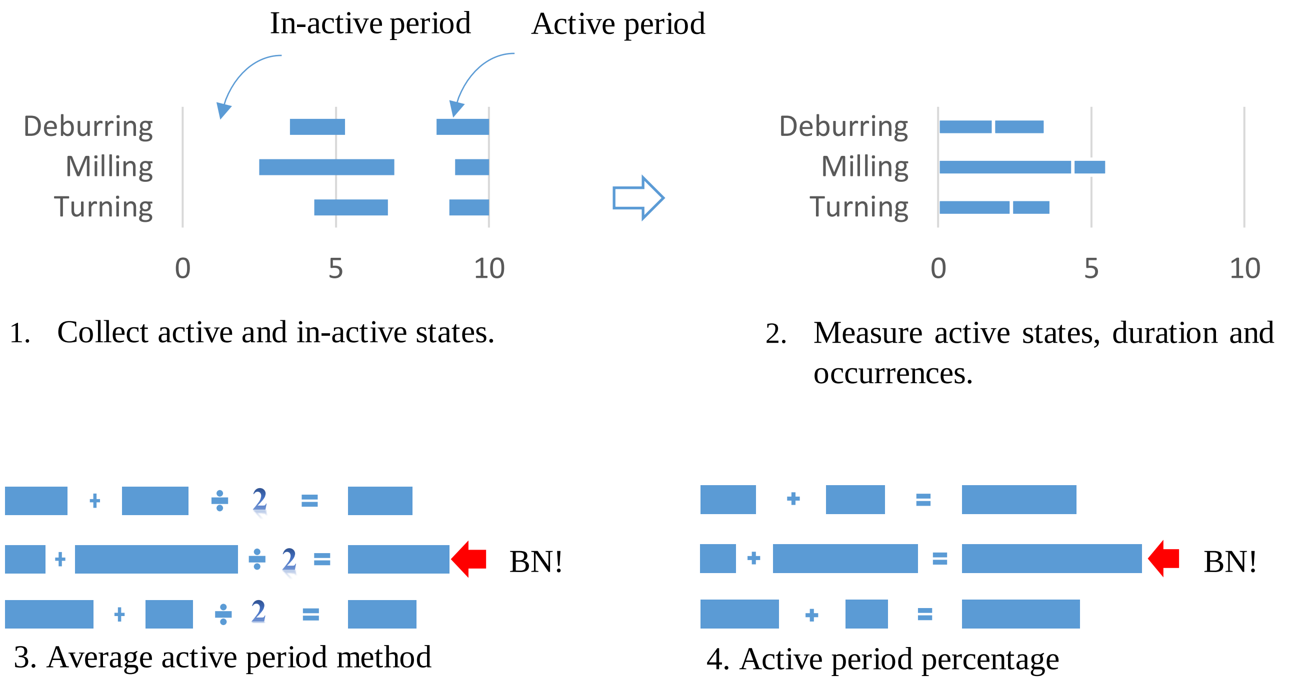


Figure 1. Graphical presentation of the active period method(s).

4.2.4.1 Data requirements

The active period percentage method does not take into account when the machine had its active period but only the times. That is, it does not need the timestamps of the machine state but only the actual time. As for the average active period, since the number of active period should be counted the time stamps are needed to see if several working cycles or disruptions make one active period.

4.2.5 Shifting Bottleneck

At any given time, a machine's state could be either active or inactive. Roser et al. (2001) defines an active state as the machine either producing or being interrupted by a breakdown, setup or similar. An inactive state is all other states where a machine is waiting for another machine, that is when it is being blocked or starved.

The machine with the longest uninterrupted active period at any given time instance is the bottleneck at that moment. The longer a machine is active without interruption, the less excess capacity it has and the more likely it is to limit the system performance. A machine which is waiting on another machine can never be the bottleneck. Where two machines with the longest active periods overlap, the bottleneck is shifting between those two machines. Then, the total time a machine is sole and shifting bottleneck respectively is summarized over a period of time to get the bottleneck machine. (Roser, et al., 2001).

An advantage of the shifting bottleneck method is that it is possible to use on a various number of systems, including complex systems with parallel processes, operators and AGVs (Ibid).

In recent years, there have been attempts to implement this method as a real-time algorithm able to detect the bottlenecks automatically for any given period. Subramaniyan et al. (2016) developed a data driven approach that is briefly described in the result chapter.

4.2.5.1 Data requirements

As far as data is concerned, the active periods per machines as well as the time-stamps for the active period continuously during the timespan to be analysed is needed. Alternatively, the inactive periods (when the machine is blocked and starved) could be used to derive the active periods. In practical situations, this could for instance be collected from the manufacturing execution system (MES) (Subramaniyan et al. 2016).

4.2.6 Average waiting time

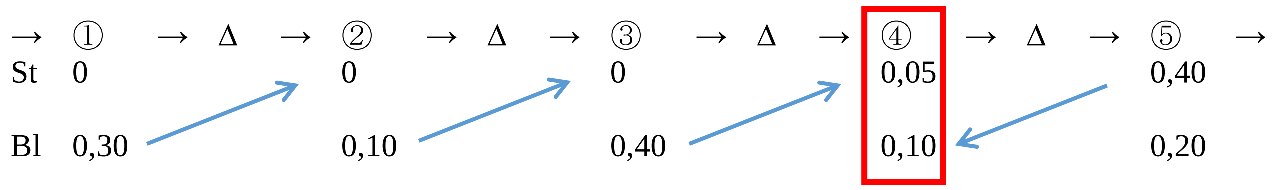
It is possible to determine the bottleneck through the average time a job is waiting for the machine. That is, the average time in queue before the machine. The machine with the longest average waiting time is considered to be the bottleneck (Betterton & Silver, 2011). The method has some limitations when dealing with system containing finite buffers and are only applicable to processing machines and not transport processes, operators etc. (Roser et. al., 2002).

4.2.6.1 Data requirements

Apart from measuring the average waiting time in the queues, it can be calculated by knowing the average number of parts in the system and the mean rate of arrival to the queue according to little’s law (Råde and Westergren, 2004).

4.2.7 Arrow method

If the time the machines are blocked and starved respectively are known, the bottleneck machine and even bottleneck buffer (the buffer most limiting to the system) can be found by comparing the figures for the machines next to each other. For illustrative purposes, it is common to draw arrows which have given the method its name. (Betterton & Silver, 2011; Li and Meerkov, 2009).



Δ - Buffer ①- Machine → - Flow

Figure 2. Graphical description of the arrow method. A graphical illustration of the arrow method. The arrows are drawn from the larger to the smaller value of the blocking and starving fractions. Where the arrows meet the most likely bottleneck(s) are. ***Source: Adapted from Li and Meerkov (2009).***

As for finding the bottleneck buffer it is defined as the buffer immediately upstream of the bottleneck machine if that machine is more starved than blocked, and vice versa (Li and Meerkov, 2009).

4.2.7.1 Data requirements

In order to implement the method, the starvation and blockage times or percentage of times are needed. That is, the time when the machine cannot process even though it is available due to it lacking parts upstream or having a full buffer downstream and not being able to unload its current part.

4.2.8 Inter-departure time variance

Inter-departure time is defined as the time from the instance a part leaves the machine to the instance the next part leaves the same machine (Lagershausen and Tan, 2014) as illustrated in figure 1.

A bottleneck tends to be less frequently starved or blocked by other machines as there will be a queue in front of the bottleneck, and empty buffers downstream. Due to this properties, Betterton and Silver (2011) proposed using the variance of the inter-departure times to find the bottleneck. As the non-bottlenecks will at times be limited by the bottleneck resource the inter-departure times, or the times between jobs, will have a higher variance as it includes waiting times as well. The bottleneck on the other hand will have a lower variance. That is, a more even flow of jobs. Variance, s^2 is calculated according to equation 1.

$$s^2 = \frac{\sum(X - \bar{X})^2}{N - 1}$$

Equation 1. Variance.

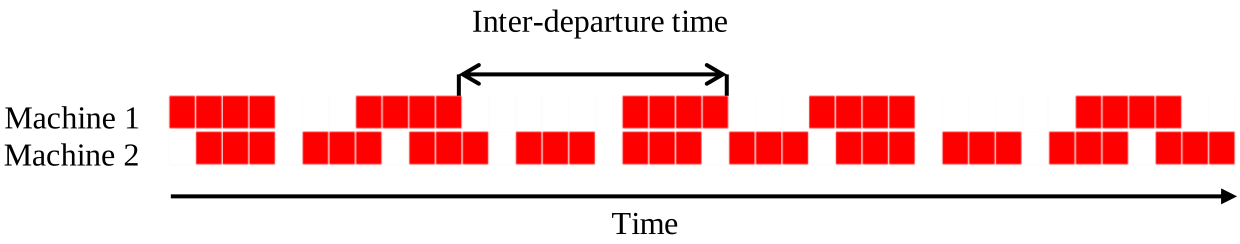


Figure 3. Illustration of the inter-departure time variance method.

4.2.8.1 Data requirements

To implement the method, either the inter-departure times directly measured for the period to be analysed or the time-stamps for the cycles of said period are needed.

4.2.9 Bottleneck walk

As an answer to many of the drawbacks with data driven and theoretical models for finding bottlenecks, Roser et al. (2015) proposed a method to be used directly on the shop floor called the bottleneck walk. By observing inventories a probable bottleneck can be found as, the buffers tend to be full upstream and empty downstream as seen from the bottleneck. Therefore, it is possible to see the direction of the bottleneck without any calculations or statistical analyses. By also analysing the state of each process, further accuracy can be achieved as a process can never be a bottleneck while it is waiting for another process. It can also tell why the machine most likely is the bottleneck as for instance a machine always running at the observation more probably is a bottleneck due to its high cycle time whereas a machine that is set up or having a breakdown probably is a bottleneck for those reasons. (Roser et al., 2015).

Roser et. al (2015) specifically recommend not to automate this process with automatic reporting of buffer levels as there is a value in manually observing the process but the method would still work.

4.2.9.1 Data requirements

In order for the method to work, the buffer levels have to be visible at random time intervals.

4.3 Summarizing table of the bottleneck detection methods

Method	**Input**	**Output**	**Time-frame**	**Reference**
Lowest production rate	Cycle time alternatively production rate.	A ranking of the machines theoretical capacity.	Real-time	Lim, Kuo and Meerkov, 1996.
Utilization	Time spent producing during the period to be analyzed.	The utilization, or fraction of the total time the machines have spent on producing.	Historical	Hopp and Spearman, 2000.
Average active period	The active period with time stamps during a continuous period.	The average active periods for the machines and thus the ranking of most likely bottleneck.	Historical	Roser et al. 2003.
Active period percentage	Time the machine is active or inactive. No time stamps required.	The fraction of time the machines have been active and thus the ranking of most likely bottleneck.	Historical	Roser et al. 2003.
Shifting bottleneck	Machine states (active/not active) with timestamps during a continuous period.	The BN at any time instant. This can be translated into number of time units for an arbitrary period and hence the fraction of time each machine is the BN.	Real-time	Roser et al. 2001.
Average waiting time	Waiting time and number of instances of waiting.	The machines with the longest average waiting time and thus the least likely bottlenecks.	Historical	Roser et al., 2002.
Arrow method	The fraction of time each machine has been blocked or starved.	The most likely bottlenecks. If there are several bottlenecks they can be ranked according to an equation.	Historical	Meerkov and Li, 2009.
ITV	Inter-departure times.	A ranking of the machines ITV where a low variance is associated with likeliness of being a BN.	Historical	Betterton and Silver, 2011.
Bottleneck walk	Buffer levels and machine status at randomly selected intervals.	Bottleneck(s) and why it most likely is a BN.	Real-time	Roser et al., 2015.

Table 1. Summary of the bottleneck detection method, their data requirements and their results.

4.4 Comparison of bottleneck finding methods

When selecting the right method for the application, a trade-off is usually made between accuracy and usability which also includes data requirements. Some methods like the shifting bottleneck method have a high demand in rich and accurate data while also being complicated to implement both manually and automatically while others are much easier. Below, a comparison of the methods pros and cons respectively is presented. Note that the comparison is for general purpose only, not tailored for this particular thesis.

4.4.1 Lowest production rate

Advantages

The method is easy to understand, the slowest machine is the bottleneck. On the shop floor, cycle times are usually available although not always reliable (Almström and Winroth, 2010). It is easy to acquire with a stopwatch, and the analysis is very simple. It can also be possibtle to determine the bottleneck before installing the line as the cycle times are often a part of the requirement specification.

Disadvantages

The method does not reflect reality as disruptions happens both for the machines and the surrounding system. Works best for applications with constant cycle times such as numerically controlled machines. Difficult to get average bottlenecks over time.

4.4.2 Utilization

Advantages

Can be used on systems with varying cycle time as it uses the accumulated time. Reflects reality better by using the actual time the machine have produced. Low data requirements.

Disadvantages

Does not fully reflect reality as disruptions are usually excluded. As it is based on average, it cannot give the real-time bottleneck at one given instance.

4.4.3 Average active period

Advantages

Intuitive, the machine which spends the longest time without waiting for another machine on average is the bottleneck. It is based on the same data as shifting bottleneck meaning that it can easily be implemented as a supplement to that.

Disadvantages

High data requirements: It requires continuous data for every time instance. Difficult analysis as multiple active states (such as working cycles) will or will not make up one active period depending on the time between them.

4.4.4 Active period percentage

Advantages

The method has been verified as accurate for analysing longer time-spans and is commonly used in the academia. It is easy to implement and use as it only needs the sum of time the machine has been active (which usually is easily calculated using for instance Excel). It can also be seen as very intuitive as the machine with the most “spare time” is the least likely bottleneck.

Disadvantages

The disadvantages for the method is that it needs a big sample size to be valid. As the name suggests it is based on an average meaning that it cannot give the bottleneck for a certain time instance.

4.4.5 Shifting bottleneck

Advantages

As the name suggests the method can detect not only static bottlenecks but also shifting. That is, it can tell when the bottleneck is shifting between two resources. It works for any type of resources including operators or AGVs and is real-time based meaning that it can tell which resource is the most likely bottleneck at any given time time.

Disadvantages

The method requires very detailed data on a continuous basis with both the active period as well as the time for which the active period was. Implementing the shifting bottleneck in practical situations require some kind of automation and/or advanced programming. When explained to the people in the production it was not seen as intuitive compared to the other methods.

4.4.6 Average waiting time

Advantages

The average waiting time have a wide range of application as it can be applied even to systems without buffers. It can give the momentary most likely bottleneck given the current total waiting time for each resource.

Disadvantages

The method is not suitable for systems with finite buffers as their waiting times have a maximum limit and other machines can be blocked by the bottleneck and hence get a high waiting time. It is also difficult to apply retrospectively.

4.4.7 Arrow method

Advantages

The arrow method has low data requirements as it only needs the time for which the machine is blocked and starved respectively. It is intuitive as blocking and starving properties is often used as indicators to find the bottleneck. Furthermore, the method can easily be automated or used manually.

Disadvantages

Getting the starvation and blockage separately is not always possible from an MES system, only the actual waiting times combined. It also needs data from a period of time and cannot give the bottleneck in real time.

4.4.8 Inter-departure time variance

Advantages

The inter-departure times is often easily acquired in the MES system as the only data needed is the cycles and when they occurred. It is easy to implement directly in for instance Excel and is very intuitive.

Disadvantages

Apart from the presented paper by the authors of the method there is not much evidence that the method actually works.

4.4.9 Bottleneck walk

Advantages

The bottleneck walk does not require any data collection at all and is based solely on observations on shop floor. It is very intuitive as buffer levels is a known indicator of bottlenecks and can be used by anyone from an operator to a production engineer. The method can to some extent detect shifting bottlenecks, at least if the analysis is made frequently. Also, it forces the practitioner to walk in the production system and find other problems.

Disadvantages

The method is time consuming as it requires multiple observations throughout a day even though every observation does not take that much time. It is difficult and not practical to use on historical data. Also, it is only applicable to processes having a visible queue and a single queue for one given resources.

4.5 Evaluation of bottleneck methods

In order to publish a paper with said model in a refereed journal, the author have to prove its validity for a number of experts in the fields. One way of doing so is through a simulation in a controlled environment (i.a. Roser et al. 2001; Betterton and Silver, 2011) followed by simulation and results from a reported case study based on industrial data (Li et al., 2009). In at least one case the simulation was based on an actual physical line from an automotive company (Gopalakrishnan et al., 2016). However, to the authors' knowledge very few tests or comparisons with extensive studies based on real industry data have been performed to this date.

When proving the models the simulation is usually run for between 100 hours (Roser et al. 2001; Li et al. 2009) to over 1500 (Betterton and Silver, 2011). However, even though some methods like the shifting bottleneck method (Roser et al., 2001) claim to work for any given time and therefore shorter time spans there have to the authors' knowledge not been verified and proven neither with simulation nor historical data. Especially in a system producing a wide range of different products, taking an average over 100 hours would be insufficient as the bottleneck will most likely shift naturally between products. Therefore, in order to take action it should be known which machine is the bottleneck for any given day, shift or even batch.

4.6 Key performance indicators

The goal of any organization is to make money (Goldratt and Cox, 1993). It is however very difficult to run an organization solely based on that measurement as it is difficult to translate into daily operations (Ibid). On an executive level KPIs such as return of investment, net profit and cash flow are used to control the company. Increasing the net profit while increasing the return on investment and cash flow is equal of making money (Ibid). Naturally the profit should be in relation to the money invested, and a good profit for a small organization with three employees would be very unsatisfying for a multinational business. On a plant level for a manufacturing organization, these measurements don't mean very much though (Ibid). This have led to the developing of a series of more specific KPIs which are presented below.

4.6.1 Selecting KPIs

KPIs are important for identifying improvement potential as well as daily operations management in the industry. They can be defined at any level from plant down to individual processes and involve areas from maintenance and energy consumption to more process related areas such as quality and throughput. From the KPIs improvement potential can be found either through benchmarking to similar plants and processes or by looking at the correlation between the KPIs and a process parameter (also called signal) and thereby optimize it. (Lindberg et al., 2015)

Lindberg et al. (2015) suggests a methodology for selecting the right KPIs for the process where the correlation between process signals and the KPI are evaluated. After selecting signals to log and download historical data, the data is then adjusted to only include data from running the plant at normal conditions. After this follows a screening process to search for signals or signal combinations that the KPI improves, and verification that a change in the signals actually yield an improvement in the KPI. As a correlation analysis, the squared sum of the difference of all the signals and the proposed KPI is calculated (equation x).

$$F(c) = \sum_{t=1}^{N} [KPI(t) - f(y(t), c)]^2$$

Equation 2. Correlation analysis to find out validity of KPI.

4.6.2 KPIs in manufacturing industry

4.6.2.1 Throughput

Throughput can be defined as “the rate at which the system generates money through sales” (Goldratt and Cox, 1993). If something is not sold, it is not throughput until it is. By only looking at the actual throughput, you risk building up a lot of inventory of products which are not sold and maybe never will be. And of course, this does not help the company making money.

According to the Lean philosophy, there are many internal customers in a process (Liker, 2004). Hence, throughput can be defined for a sub-part of the production system as well such as a line or even a single machine in a line.

4.6.2.2 Inventory

“Inventory is all the money a system has invested in purchasing things which it intends to sell” (Goldratt and Cox, 1993).

4.6.2.3 Operational expense

“Operational expense is all the money the system spends in order to turn inventory into throughput” (Goldratt and Cox, 1993). Traditionally, companies have been obsessed with trying to cut costs without realizing that an optimization (or rather sub-optimization) in cost can have devastating effects on the other more important metrics. This short-term management strategy have been challenged in recent years, for instance by the Lean ideology. Liker (2004) states for instance that Toyota, while having a focus of waste reduction are more concerned about the long-term performance. Even though lower operational expenses could be achieved by increasing batch sizes and therefore throughput, this would not contribute to the long-term goal.

4.6.2.4 OEE

Overall Equipment Efficiency, OEE is a concept emerged from the total productivity maintenance in 1988 (Ylipää et al., 2016). It can be defined as the fraction of time spent producing approved quality to the planned production time (Almström, 2012). There is however a big confusion on how to actually calculate this figure. Many companies use the time spent on a batch in relation to the time reported as the ideal time in the MRP system as a way of calculating OEE, but as there usually are a big mismatch between the true ideal time and the time reported in the MRP this is far from the original definition (Almström and Winroth, 2010).

OEE can be calculated by multiplying the availability (A) operation efficiency (O) and the quality yield (Q) according to equation 4 (Almström, 2012).

$$OEE = Availability \times Operational\ efficiency \times Quality$$

Equation 3. OEE - Overall Equipment Efficiency.

4.7 Bottleneck management

Once you have done the analysis and found the bottleneck, being a momentary or average bottleneck, the important question is what to do with this information. This chapter aims at explaining both how to work with bottlenecks in the operations management, on a short term as well as long term.

4.7.1 Short term bottleneck management

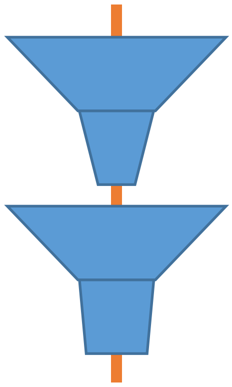


Figure 4. As a short-term strategy, it is important to make sure that the system (here represented by the two funnels) is used to their full capacity. That is, that they are scheduled all the time, not working with reduced speed and so forth.

Before taking actions to widen the bottleneck and increasing the capacity, one can make sure that the current bottleneck is utilized at its fullest potential at all the available time possible as illustrated in figure 4. Goldratt and Cox (1993) states that an hour lost in the bottleneck is an hour lost in the system whereas an hour won in a non-bottleneck is just a mirage. As a consequence of this, an hour lost in the system will have the financial impact not only on the actual machine but the whole system. That is, non-utilized time in the bottleneck cost as much as shutting down the plant as a whole.

Even though the first thing companies might do when they find out a constraint in the production is to invest in additional capacity, it is probably not needed as a first step. Pegels and Watrous (2005) proved that just by reallocating the capacity of the constraining resource, in that case the setup-operations for a moulding process of an automotive supplier an improvement of 26 percentage could be achieved. That is, having the bottleneck determine the schedule of the whole plant one can make sure to use its full potential. They also added extra capacity by allowing the setup-personnel to work overtime during extra busy period, without having costly extra capacity (personnel) during idle times.

Lozinski and Glassey (1988) goes one step further and propose a "bottleneck starvation avoidance policy. The objective of such a policy is to make sure that the critical processes, the potential bottlenecks, never starve. Since the bottleneck limits the plant output, the focus should be on avoiding anything that limits the bottlenecks output. To help with this, they propose a series of equations as well as a methodology for how to free up resources at the bottleneck. This can be reducing downtime, reducing time spent producing test batches etc., increase buffer before the bottleneck and improve by installing new capacity or making sure that the machine produces more efficiently when it is producing.

4.7.2 Long term bottleneck management

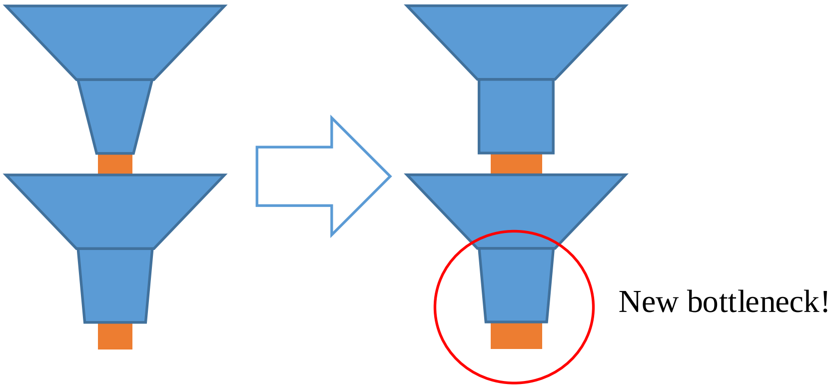


Figure 5. As the utilization of the bottleneck becomes larger there might be a need for increasing its maximum capacity. This can be for instance investing in new equipment, and is here illustrated by increasing the diameter of the bottleneck funnel.

While a better utilization could be sufficient for a long time, at some point an increase in capacity is either the only option or the most economical option as getting the last percentages of utilization could be very expensive. At Siemens in Dresden, Germany, Brown et. al. (1998) did a case that resulted in a 30% reduction in manufacturing cycle time. To achieve this, they first changed the batching policy for the bottleneck and thereby increased its utilization as a short-term bottleneck management. As this was insufficient for achieving the target reduction, they invested in a method change as well as increasing the staffing by one operator per shift as further long-term improvements.

Both Goldratt and Cox (1993) and Brown (1998) highlights the importance of realizing that the bottleneck might very well shift after improvements are made, as illustrated in figure 5. Goldratt and Cox (1993) therefore suggests a method of five steps for working with bottlenecks, where the first four steps are to identify and elevate the constraint but the last and maybe most important step is to go back to step one as you don't want inertia to become the next constraint. That is, after performing the loop of finding and improving the bottleneck one must make sure that the bottleneck still is the bottleneck after improvement (or if you will, that the improvement was insufficient).

4.8 Correlation analysis

Analysis is a method for determining the relationship between two or more variables. It usually starts by plotting the variables against each other in a scatter diagram to determine if there is a relationship between them. An example of such a plot can be seen in chart 1. It is important to note that in almost all applications, the true relationship is not found but a linear approximation is used as substitute. (Montgomery and Peck, 2012).

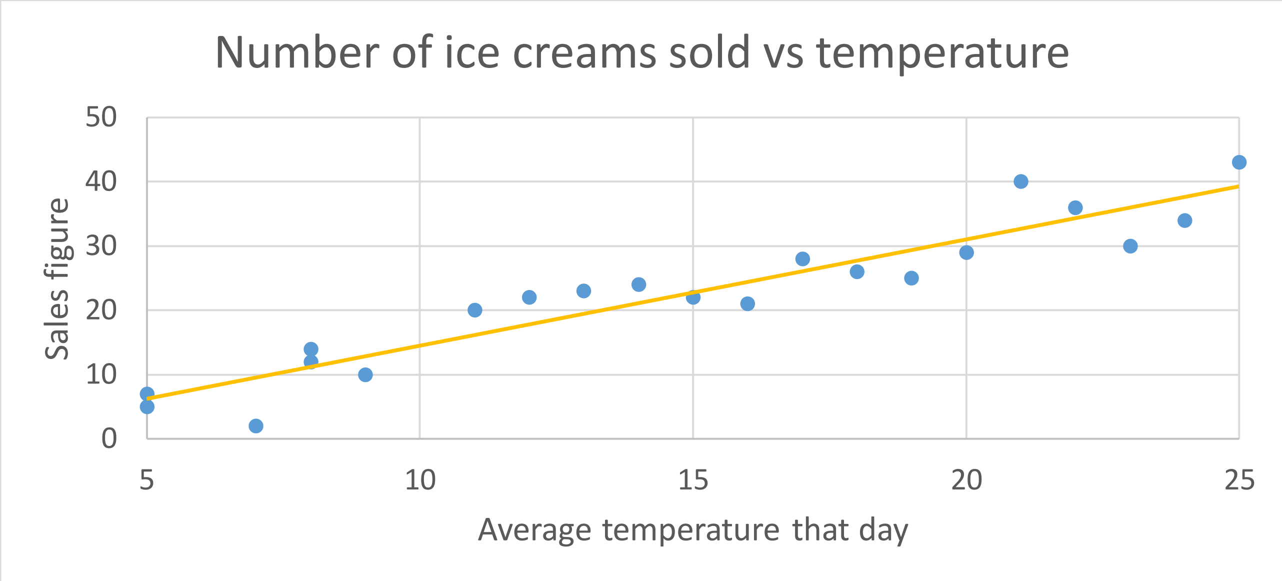


Chart 1. Example of a scatter plot with a linear average approximation line.

4.8.1 Different types of studies

4.8.1.1 Retrospective

In order to determine if there is a relationship among the variables, some kind of study have to be performed. According to Montgomery and Peck (2012) there are three types of studies depending on the application and data available and possibility to manipulate the process to get the data. These are retrospective studies, observational studies and designed experiments.

The retrospective study is as the name suggests a study of previously collected data in order to find out a relationship and the correlation. This effectively minimises the cost of the study as previously collected data is used. It also has the benefit that it doesn't tamper with the process in the way that the other studies inevitably does. However, extreme caution on how to use the data should be used and regardless the study usually gives questionable results and lead to wrong conclusions. This is mainly due to the fact that the data often is of questionable quality, and more importantly, that it is used in a way it is not intended to be used in the first place. According to Montgomery and Peck (2012), the data that is collected with greatest accuracy is usually the one which is convenient to collect. Trying to draw conclusions based on that data, and even worse, trying to use the collected data as surrogates for the data that is really needed have led to too many invalid conclusions over the years. (Montgomery and Peck, 2012).

4.8.1.2 Observational

Similar to the retrospective study but carried out in real-time is the observational study. Instead of trying to draw conclusions based on historical data the process is observed without disturbing the process more than necessary. One of the main benefits to the retrospective study is the ability to add measurements and observe interesting phenomena that occurs, as well as the luxury of being able to define the proper measurement variables. (Montgomery and Peck, 2012). For instance, the variability in the process might be explained by changes in the outside temperature and if that is not measured in the retrospective study faulty conclusions might be drawn. In the observational study, there is at least a chance to detect such phenomena. One of the drawbacks with an observational study is however that they take a lot more time to perform as the data has to be collected. In the retrospective study, years and years of data might already be available at the fingertips of the researcher whereas that would take years and years to collect in an observational study.

4.8.1.3 Designed experiment

The last and best (Montgomery and Peck, 2012) collection strategy is to make a designed experiment. In such a study, one can not only define the responses but also manipulate the process in in order to properly find the effects associated with each variable. In the two previous examples, the process might be strictly controlled leading only to small deviations in the parameter to measure (for instance temperature or speed). Drawing conclusions based on those might then be impossible as the natural variation in the process is larger than the variation due to the variables.

4.8.1.4 Example

As an example, let's say that you want to find out the effect of speed and tire pressure on the fuel consumption in the car. In the retrospective study, you would probably only have those two variables recorded over time. If the car is mainly driven on highways with the speed varying between 100 and 110 km/h and the tire pressure is set to be 2.0 bar it is hard to draw any conclusions. Other factors that might affect more such as air temperature is not accounted for, and for the sake of argument impossible to find out afterwards. In the observational study, the speed and pressure is still fixed but you are able to define your own variables such as tire temperature, outside temperature and so forth to account for them and see what variables really affect the fuel consumption. By doing a designed experiment, you allow the speed and pressure to take more extreme values to see how big effect the speed, tire pressure and more importantly both of them combined has.

5 Methodology

In this chapter, the methodology used in the thesis is presented. As a part of the research an industrial case study was carried out which is explained in detail.

5.1 Industrial test study

In order to test the hypothesis, an industrial case study is performed at the transmission manufacturing department at Scania CV, using the data from one of their lines. Below the data, methods and different steps are further explained.

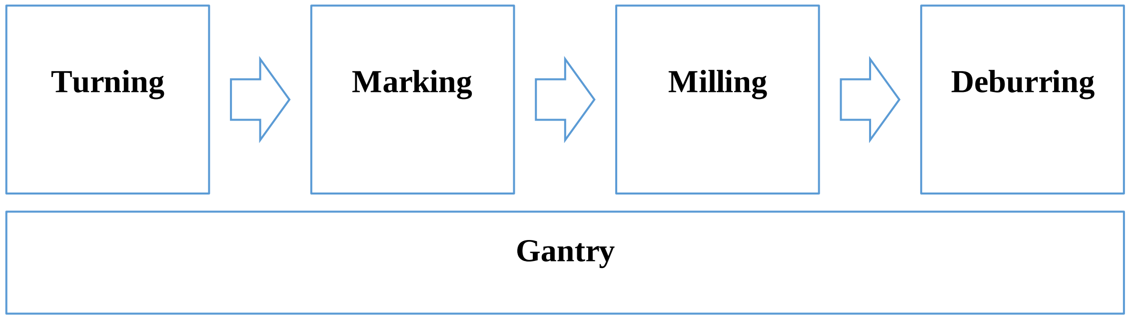


Figure 6. The production system to be analyzed in the industrial case study is a serial line containing of four machines and one gantry, where the last machine is shared with another identical line.

5.1.1 Test lines

Selected for the thesis was a typical serial line containing of four machines; one turning machine followed by a marking machine, a milling machine and a deburring machine. Serving all of the machines was a gantry as explained in figure 6. The deburring machine is shared among two identical lines where it strictly serves every other line. It can be noted in the figure that the machines do not have allocated buffers in between them but that the gantry has buffer places available for the complete line.

5.1.2 Data

The data was acquired by the Manufacturing Execution System by RS-production by Good Solutions and exported into MS Excel for processing.

Machine	Type	Art-Nr	Time stamp	Cycle Time
Milling	Pinion	132734	2017-01-19 11:45:41	301,9
Gantry	Pinion	132734	2017-01-19 11:51:06	124,2
Turning	Pinion	132734	2017-01-19 11:56:31	245,7
Milling	Pinion	132734	2017-01-19 12:01:59	301,4

Table 2. An example of the working cycles retrieved from the MES system.

Machine	Type	Art-Nr	Start Time	End Time	Disruption
Milling	Pinion	132734	2017-01-19 11:45:41	2017-01-19 11:47:41	Waiting for part
Gantry	Pinion	132734	2017-01-19 11:51:06	2017-01-19 11:54:16	Setup
Turning	Pinion	132734	2017-01-19 11:56:31	2017-01-19 11:59:29	Tool change
Milling	Pinion	132734	2017-01-19 12:01:59	2017-01-19 12:10:16	Uncategorized
Milling	Pinion	132734	2017-01-19 12:11:59	2017-01-19 12:19:16	Breakdown

Table 3. An example of the disruptions retrieved from the MES system.

5.2 Data mining

The data is analysed and mined according to an adopted version of the Cross-Industry Standard For Data Mining (CRISP-DM) method as illustrated in figure 7. That is a method used for extracting, cleaning and preparing data for decision support (Shearer, 2000). This is a widely used technique in manufacturing industry and is very flexible.

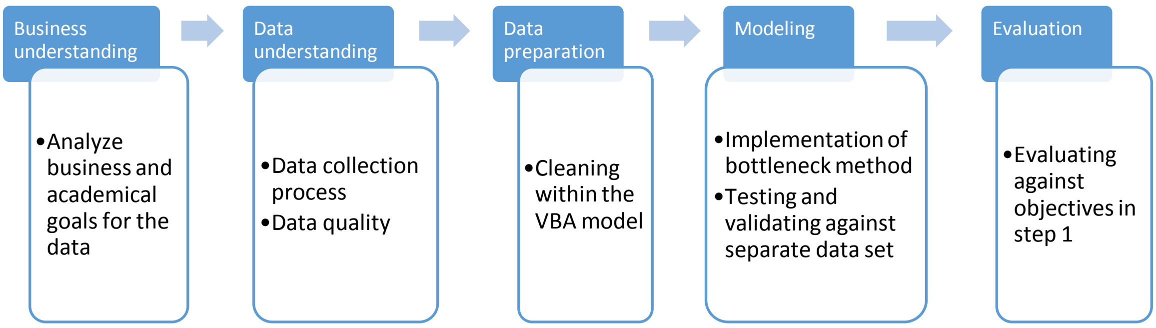


Figure 7. Application of the CRISP-DM model. ***Source:*** *Adapted from Shearer, 2000.*

5.2.1 Business understanding

The first and maybe most important step (Shearer, 2000) is to define the business objectives, that is, what the data should be used for. In the industrial test study, this was defined with inspiration from Goldratt and Cox's "the goal" (1993). Ultimately, the main objective for a manufacturing organization is to make money which it does by achieving a high throughput while simultaneously keeping inventories and operational expenses down (Goldratt and Cox, 1993).

As the project is not only an industrial project but also an academic one, naturally these objectives will be considered just as important as the business objectives. With the academic approach also follows that parts of the objectives of the data collection is already known and established by other researchers in the same field.

5.2.2 Data understanding

The data understanding contains of four steps: collection of an initial data set, description of the data, exploration of the data and verification and quality control of the data (Shearer, 2000). As the system to collect the data already was in place, the focus was verification and data quality. To do this, extensive field studies have been performed where the data is manually collected and thereafter cross-validated against the data collected by the IT-system to make sure that the data is collected as intended. It has also been verified with experts of the system to further prove its validity.

5.2.3 Data preparation

The data is prepared by exporting it to Microsoft Excel for further analysis. Rather than cleaning the data from all days without production and unscheduled time manually, this was implemented straight into the model as described below. The aim was not only to analyse the data but to the furthest extent possible automate it to enable the analysis of more data within the limited time span of the project.

5.2.4 Data cleaning

In order to get useful results, the data have to be cleaned from values outside a steady state of the production as well as non-useful ones. Although the data generally had a sufficient quality and did not require extensive cleaning, the following have been cleaned or excluded:

- ITVs over about three cycle times. Betterton and Silver (2011) didn't suggest how the data of the inter-departure times should be cleaned. However, as the method is based on whether or not there is a queue in front of the machine as it usually is on a bottleneck machine no inter-departure times above three cycle times was included as one longer disruption then will be the only significant contribution to the variation for that period of time.

- Days without production such as weekends, holidays etc. When doing the correlation analyses the data was cleaned to not include any days without production. As one day without production would have some KPIs of zero (for instance OEE), this would bias the correlation.

- Attempts of cleaning the data from days without steady state have been made but did not yield in any useful results. Days without steady state could be for instance days with long disruptions for the whole line, where the machines are up but no parts are being produced. This was accounted for by analysing the scatter plots for correlation as those days will show up as outliers.

5.2.5 Modelling

The data is modelled with a Microsoft Excel Visual Basic for Applications (VBA) script, which is further described in the results. This is partly because of the practitioners' current competence with it but also because of compatibility with the data system. Effort have been put into making the model as automatic as possible to enable more analyses.

An important part of the modelling is testing the model with respect to strength, validity and quality (Shearer, 2000). As suggested in the CRISP-DM, the model is developed using one data set and then tested and evaluated using another set of data. In the case of this study, data from another identical line and time then the data used for developing was used. Also, a lot of manual debugging and testing of algorithms to compare the output of the model have been performed.

5.2.6 Evaluation and validation

As a last step, the model is evaluated on how well it fits the objectives in step one. The validation is done as a two-step process, where the first step is to validate the data from the MES system and the second step is to evaluate the results of the model built in the previous steps.

To verify the data, extensive field studies have been performed where samples of data has been manually collected and compared to the data acquired from the MES system. This is to make sure that the cycle times and disruptions are logged according to the specifications. The reason for the disruptions are manually inserted by the operators and some samples have been made to verify this procedure.

As indicated in the previous modelling step, the model was built using one data set and then tested on a separate data set using a stand-alone data set from another line and time. This is to ensure that no systematic errors in the data set yields error in the model. Furthermore, the output of the model has been analysed and validated together with experts of the system.

5.3 Selecting KPIs

When it comes to KPIs, a trade-off has to be made between the usefulness of the KPI and how well-known and intuitive it is to the user. To the extent it is possible, the KPIs currently collected and used at the company are used in the model. Secondly, KPIs that are common and used in the industry today are used and lastly the more academic KPIs and variables will be used.

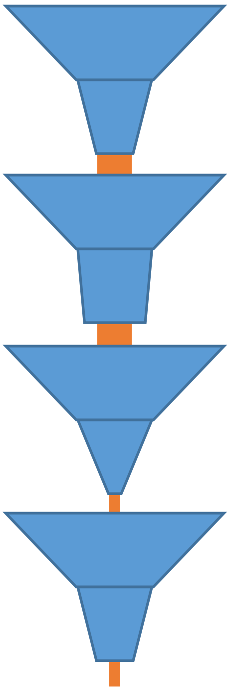


Figure 8. An illustration of the bottleneck in the system. A resource (here illustrated by funnels) can be the bottleneck due to low capacity (small diameter) or due to extensive disruptions (stop in the funnel). Note also that as the funnels are serially connected the throughput (represented by the outflow) will be limited by the funnel with the lowest capacity.

As indicated by Goldratt and Cox (1993), throughput is one of the most important KPIs for a manufacturing industry. And while this is true, on a machine level it does not make a lot of sense for a serial production line. Figure 8 illustrates the dependency among the machines, where all the machines are limited by the bottleneck. It does not matter if the other machines (funnels) have an excess capacity, the output of the sand-funnel-system will be dependent on the smallest diameter. The system can only improve its capacity by increasing that diameter.

5.3.1 Screening

To find relevant KPIs, first a screening process of the KPIs available in the MES system was performed as a multivariate correlation analysis. The reason for this is that even though the exported KPIs might not fit the agreed definitions and equations, collecting the data and calculating them manually is a time-consuming task and that a correlation will still show up in the MES data. From that, a few KPIs was selected for further analysis.

6 Results

In this chapter, the results for the thesis are presented. This includes the implementation of the bottleneck methods, the result of the bottleneck analysis and the results for the correlation analysis.

6.1 Bottleneck analysis

6.1.1 Implementation of shifting bottleneck

Using VBA, the proportion of time the machines were shifting or sole bottlenecks each day was implemented and calculated based on the algorithm proposed by Subramaniyan et al. (2016). This is done according to flowchart in chart 3 - 4. A two-dimensional array, one row per machine and one column per elapsed second was constructed according to the algorithm based on the exported data from the MES system. As active state, all producing cycles and all disruptions but “Waiting for part” was used. This is repeated for each machine in the system according to chart 4.

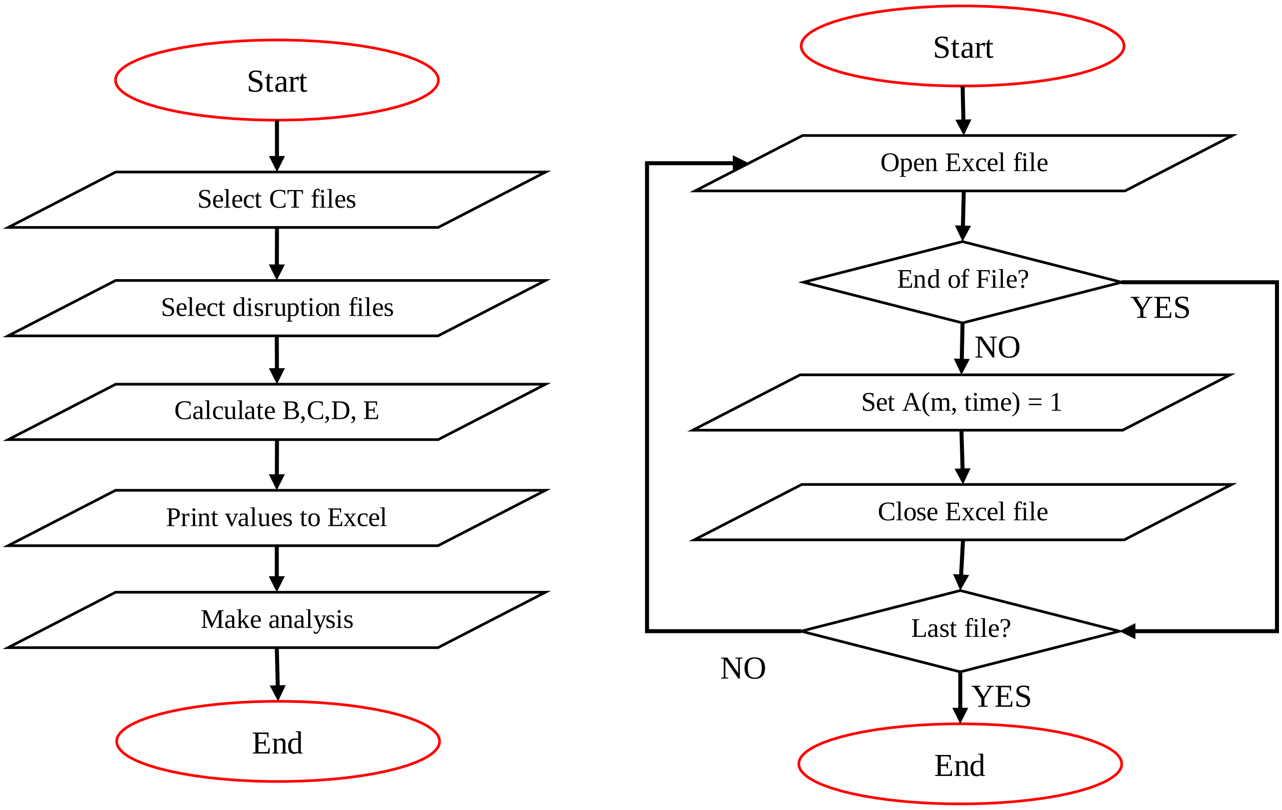


Chart 3-4. Flowchart 3 (left) for the main-script for building the B to E matrices described below and analyzing the data with respect to the bottleneck. This calls the sub-script described in flowchart 3 at “select files”. Flowchart 4 (right) for the sub script for building the A-matrix as described below. This is called from the main-script in flowchart.

Below follows an example of the matrices used for the various steps in the algorithm. Note that these are examples only as the real matrices are too

Machine/time (seconds)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Machine 1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1
Machine 2	1	1	1	1	0	0	0	1	1	1	1	0	0	0	1	1	1	1
Machine 3	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1

Table 4. A matrix. The active machines at any given time, where 1 is active and 0 is inactive. ***Source: Adapted from Subramaniyan et al. (2016).***

Machine/time (seconds)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Machine 1	0	0	0	0	0	0	1	2	3	4	5	6	7	0	0	0	1	2
Machine 2	1	2	3	4	0	0	0	1	2	3	4	0	0	0	1	2	3	4
Machine 3	1	2	3	4	5	6	7	8	0	0	0	0	1	2	3	4	5	6

Table 5. B matrix. An accumulation of the active states. ***Source: Adapted from Subramaniyan et al. (2016).***

Machine/time (seconds)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Machine 1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
Machine 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Machine 3	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1

Table 6. C matrix. Potential bottlencks. Starting from the last column, the longest active period at that instance in the B-matrix is marked as 1 and the rest 0. Where that active period starts, the process is repeated. ***Source: Adapted from Subramaniyan et al. (2016).***

Machine/time (seconds)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Machine 1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
Machine 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Machine 3	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1

Table 7. D matrix. The overlapping periods (the instances where the bottleneck shifts from one machine to the next) in the C matrix are set to 1, the rest 0. ***Source: Adapted from Subramaniyan et al. (2016).***

Machine/time (seconds)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Machine 1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
Machine 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Machine 3	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	1	1

Table 8. E matrix. The D matrix subtracted from the C matrix. That is, the instances where the machine solely is the bottleneck. ***Source: Adapted from Subramaniyan et al. (2016).***

6.1.2 Adoption of the shifting bottleneck to include shared resources

The line has the special case of a resource (the deburring machine) which is shared among two lines. While the author (Roser, 2001) mention that it works even for complex systems, he does not specifically mention shared resources. To adopt the method for this case the assumption has been that all periods independently of the product produced at that time instance are viewed as active. This is because the method only differentiates between active and inactive period where inactive is when the machine is waiting. Setting the times when the machine process parts for the other line as inactive would indicate that it was waiting and that time, but the machine can be the bottleneck for this line because of the products from the other line. Hence, the times when the machine is producing for the other line is considered active states.

6.1.3 Implementation of inter-departure time variance

The inter departure-time variance was acquired from the cycle time data according to equation 1. Due to the implementation of the MES system, waiting time was only logged for two out of the four machines (milling and turning machine) meaning that this would not be a sufficient bottleneck index at its own.

6.1.4 Process variation

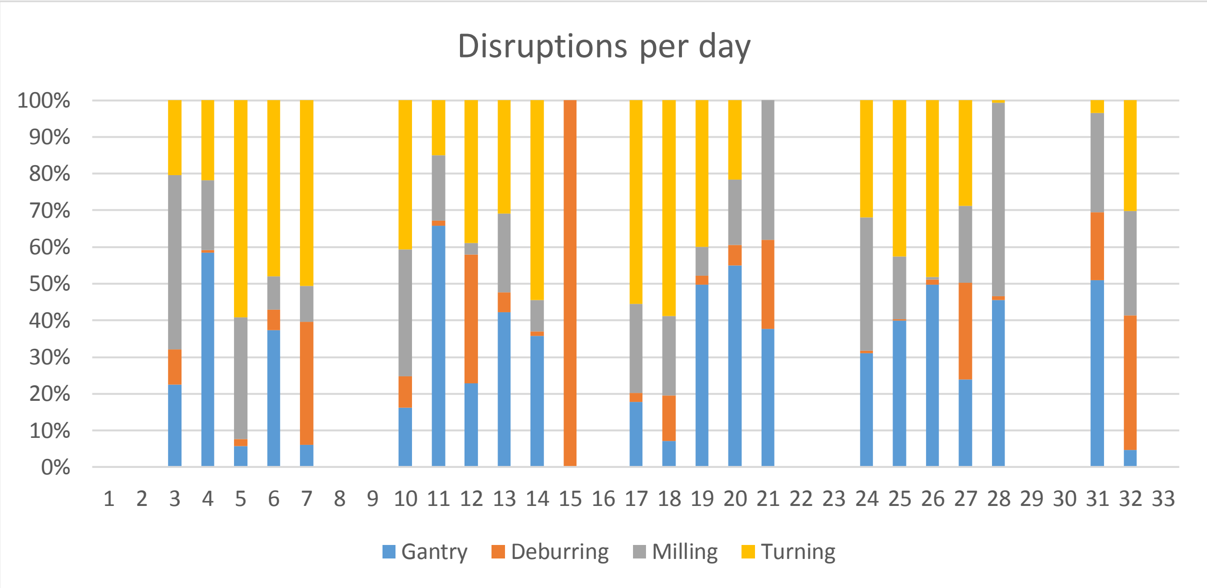


Chart 11. Fraction bar chart of the total time of disruptions per day. The machine with the highest portion/bar has the longest disruption for that day.

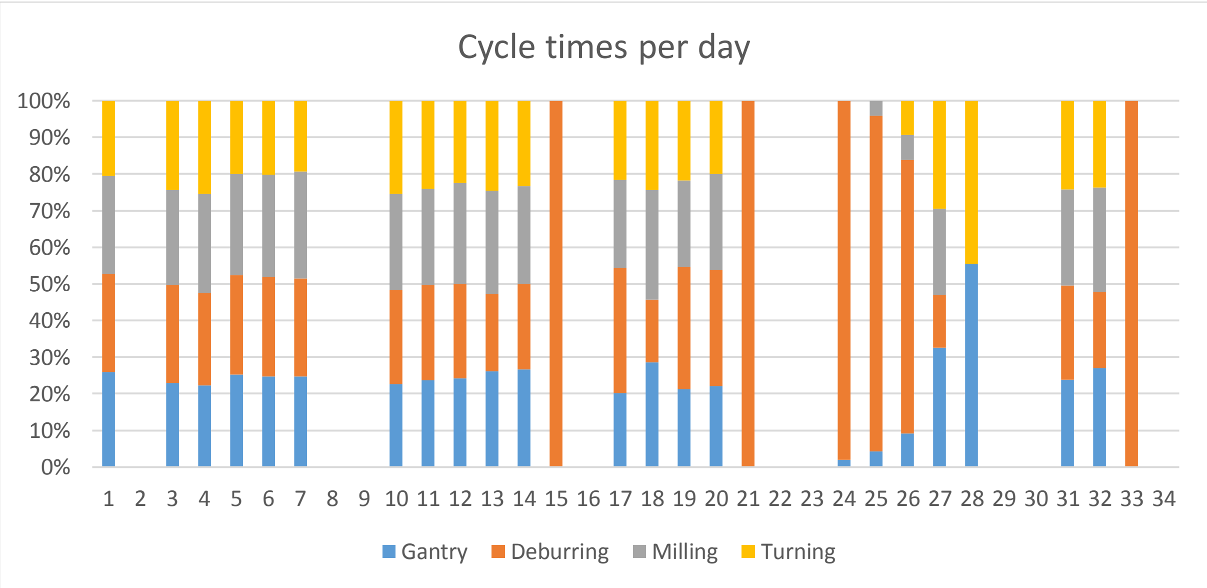
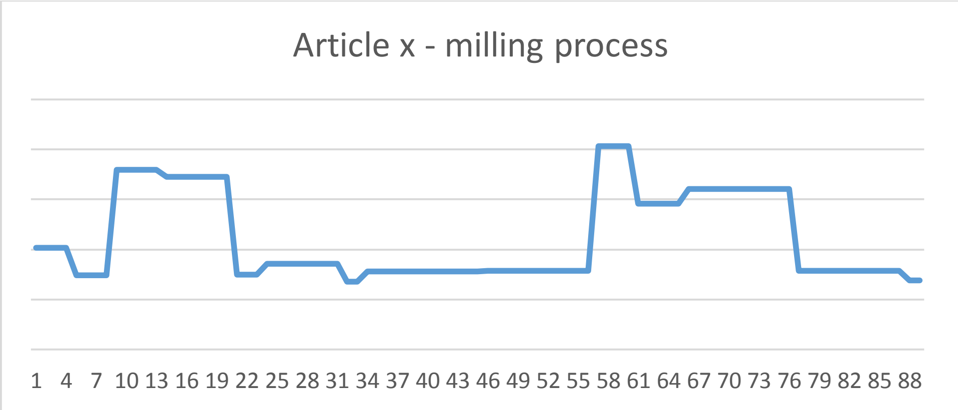


Chart 12. Fraction bar chart of the total cycle times per day. The machine with the highest portion/bar has the highest accumulated cycle time (and hence utilization) for that day. The days when the deburring machine has 100%, this line has been down and the other line which the deburring machine also serves has been up.

6.1.4.1 Variation of process cycle time



Graph 1. The variation of cycle time for the same machine and article within a batch of size of 88.

Process variation remains a big problem within the manufacturing industry and the studied line being no exception. Graph 1 shows how the cycle time varies between work cycles during one particular batch, with the difference between the highest and lowest time being up to ten percent. The exact cycle time is removed because of confidentiality.

6.1.4.2 Distribution of the cycle time vs disruptions

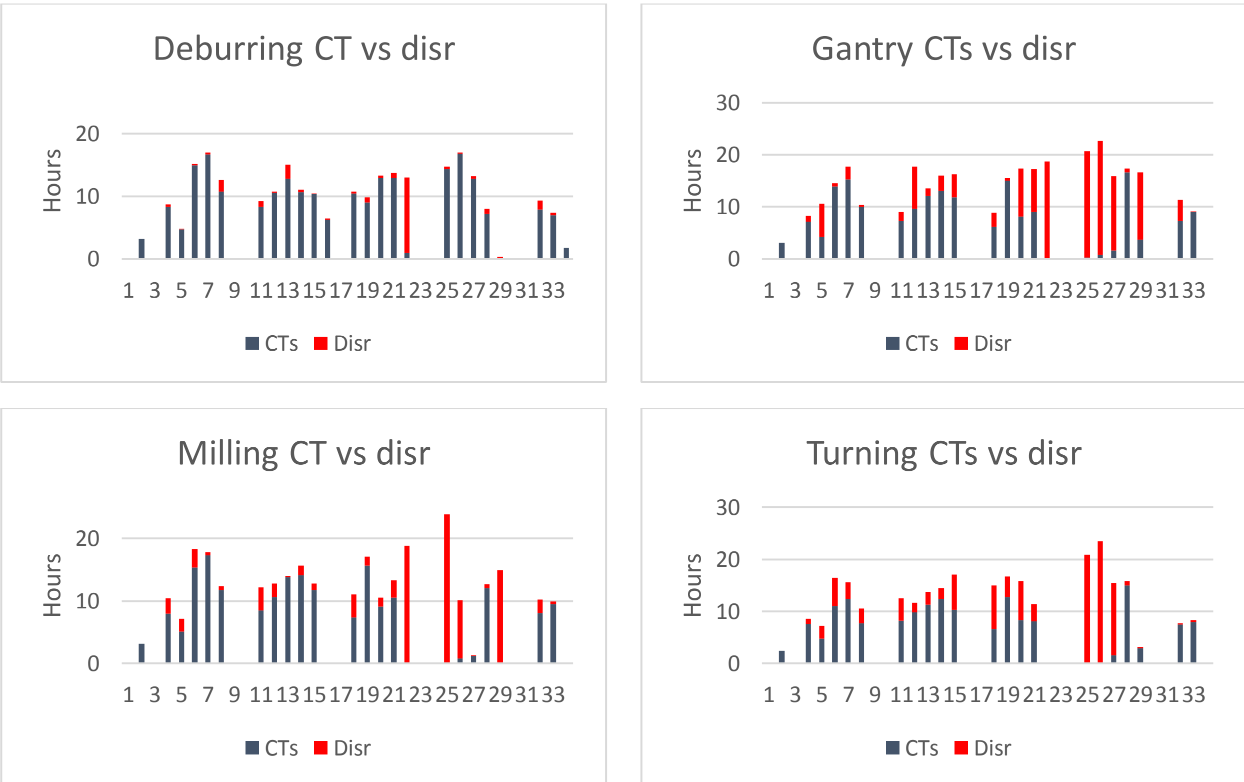


Chart 4 - 7. The distribution of the cycle time vs the disruption time for each machine in hours.

The ratio between production time and disruptions is also varying between machines as seen in chart 4 - 7. An important note is that the gantry has a relatively high amount of disturbances compared to the other machines, which quickly can become crucial as it is serving all other machines without redundancy and therefore will affect all other machines at the line.

Plot 1-6. The inter-departure times for each of the machines in one line. Note the distribution where most are around one cycle time but there are a few outliers and the logarithmic scale on the y-axis.

Scatterplot 2-6 shows a wide spread of the inter departure times, with the majority being around one cycle time for most of the machines. The plotted data is raw meaning that no cleaning have been performed and the time the machine has been standstill due to weekends and so forth is also included. When calculating the ITVs for the bottleneck analysis, the data was cleaned to only include a steady state according to the procedures in the method chapter.

6.2 Bottleneck results

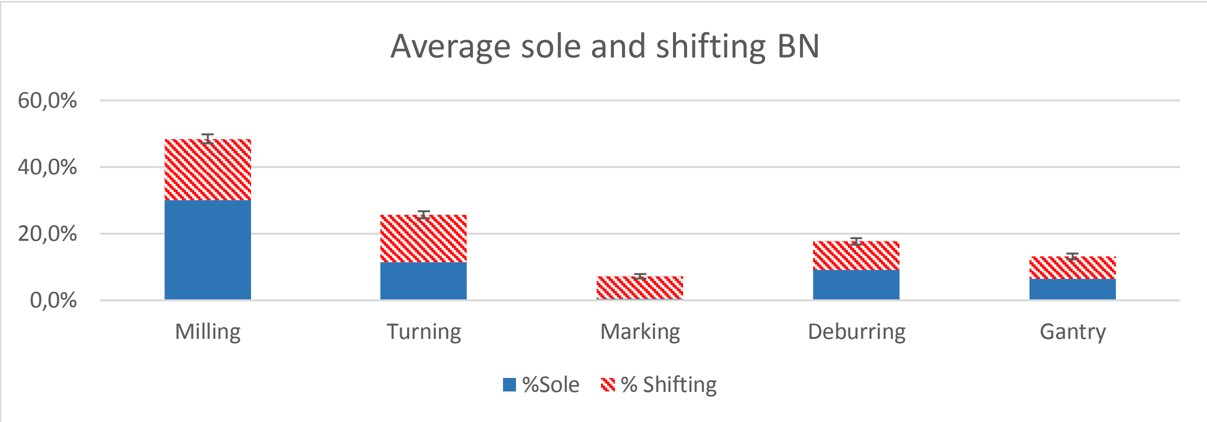


Chart 8. The total percentages each machine is sole and shifting bottleneck respectively according to the shifting bottleneck method during one of the 30 days' period analyzed.

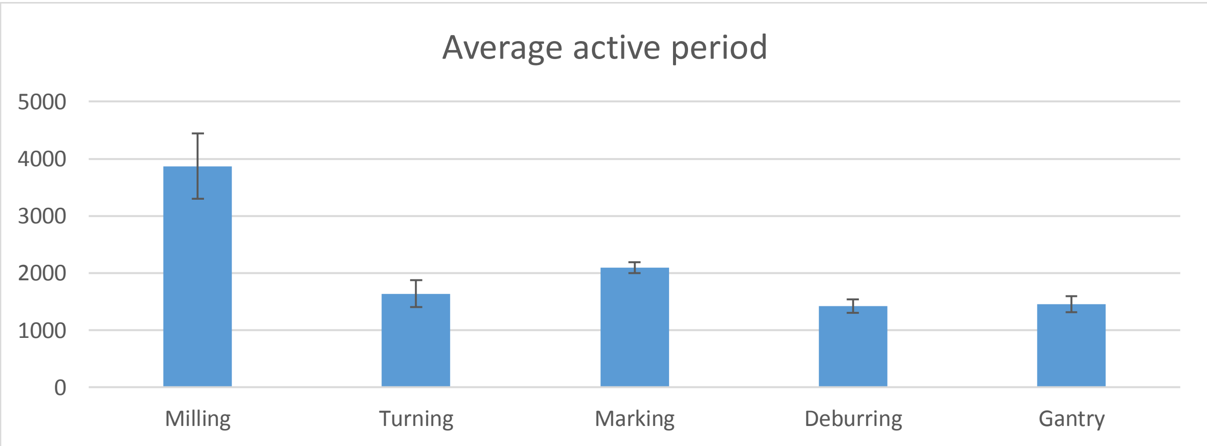


Chart 9. The average active period for each machine during one of the 30 days' period analyzed.

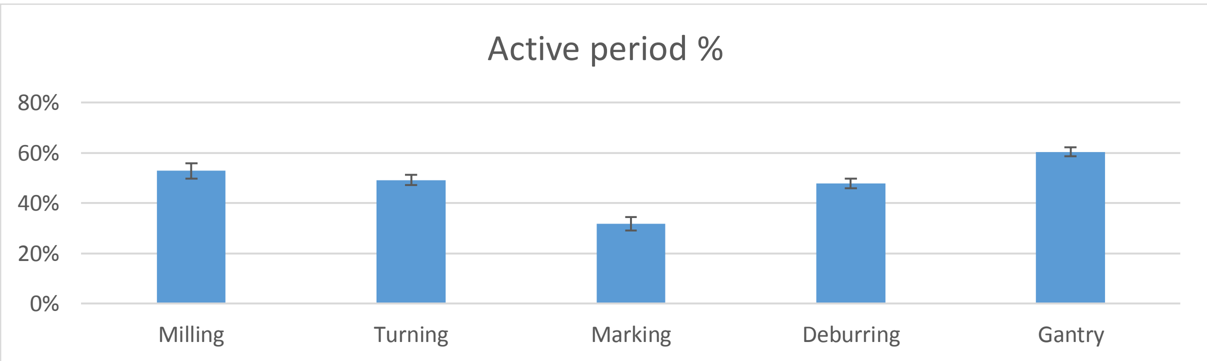


Chart 10. The percentage of time each machine is active during one of the 30 days' period analyzed.

Chart 8-10 illustrates the bottlenecks for the whole period of 30 days according to three different methods: the shifting bottleneck, the average active period and the active period percentage. The shifting bottleneck clearly shows that for the given time period the most frequent bottleneck is the milling machine. As ranking of the second and third most occurring bottleneck goes, it is hard to distinguish between the gantry and the turning machine. What is clear though, is that the marking machine is a non-bottleneck.

Also for the average active period the milling machine is the bottleneck. However, the second most likely bottleneck is the marking machine which was clearly stated as a non-bottleneck machine for the shifting bottleneck method. Between the remaining machines, i.e. the turning, gantry and deburring machine the average active period is so similar that the least likely bottleneck cannot be distinguished between them.

The active period percentage shows the gantry to be the most frequent bottleneck for the whole line even though the results are much more even between the four machines with the highest active period percentages. Just as for the shifting bottleneck method, the marking machine is ranked as the least likely bottleneck for the whole period.

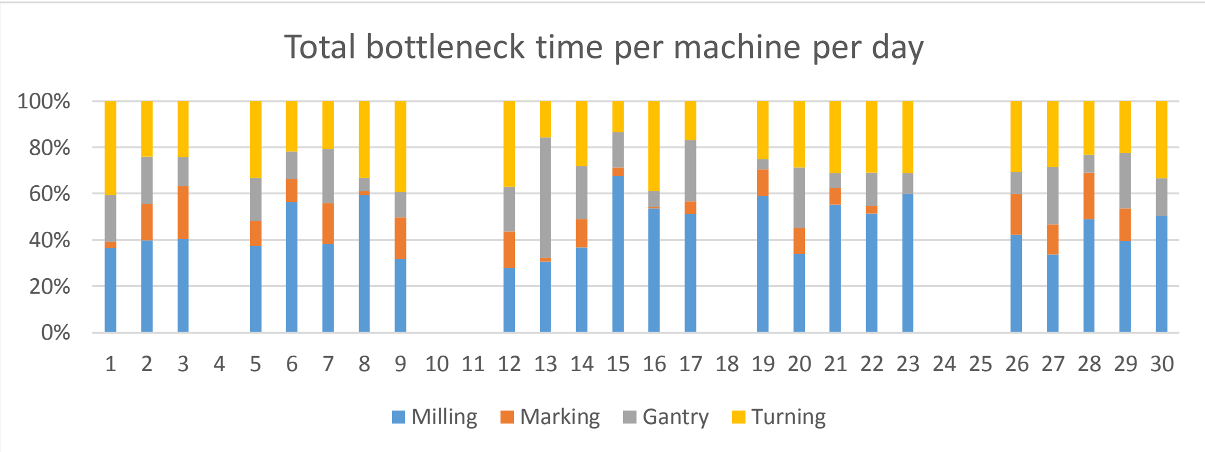


Chart 11. Fraction bar chart of the total time each machine has been a bottleneck or shifting bottleneck per day according to the shifting bottleneck method. The machine with the highest portion/bar has been the bottleneck the longest time for that day.

On a day to day basis the milling machine is the most frequent bottleneck followed by the turning machine as seen in chart 11. Note however that almost all machines are bottleneck at some point during the day. As the batches and shifts does not correlate with the days, there can be multiple batches produced on one day as well as multiple teams of operators running the machines.

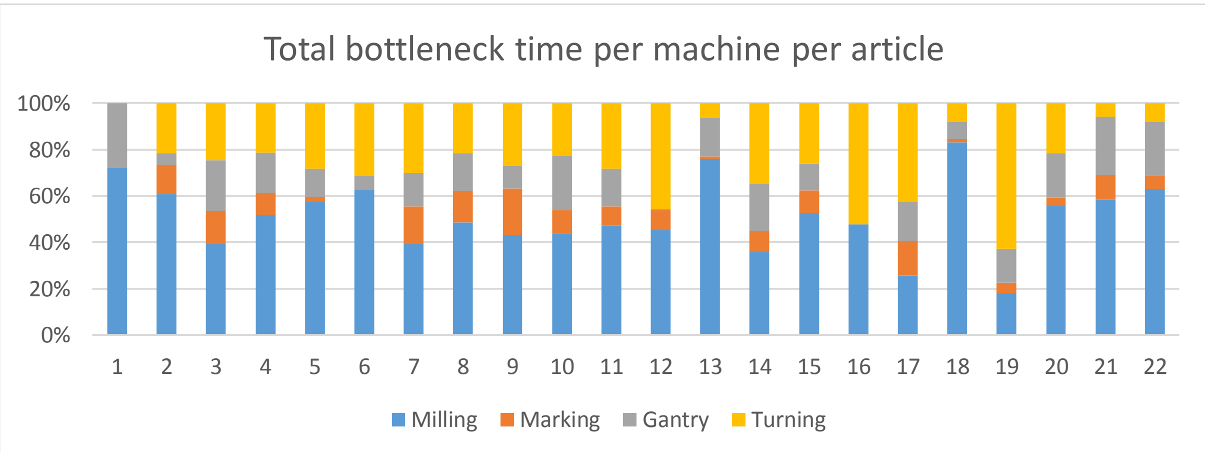
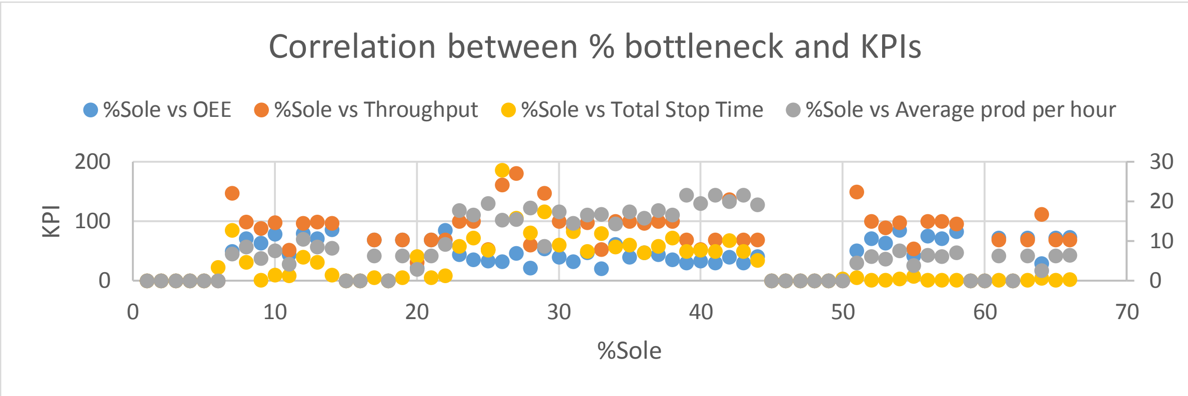


Chart 12. Fraction bar chart of the total time each machine has been a bottleneck or shifting bottleneck per article according to the shifting bottleneck method. The machine with the highest portion/bar has been the bottleneck for the longest time that article.

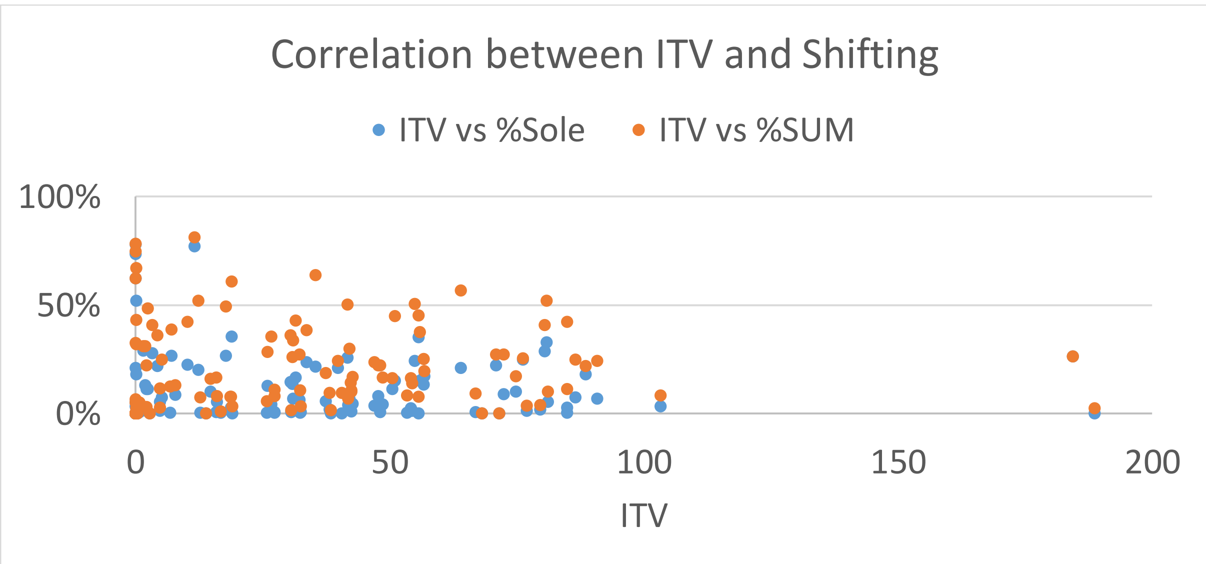
Also when looking per article the milling machine is the most frequent bottleneck followed by the turning machine as seen in chart 12. Hence, the shifts in bottleneck can at least not fully be explained by shift in articles and therefore cycle times. A more extensive analysis with the exact number of second each machine is bottleneck per article can be found in appendix. There is also a summary available for the articles that are produced more than one time during the 30 day period and how the bottleneck figures are varying between those runs.

6.3 Correlation results

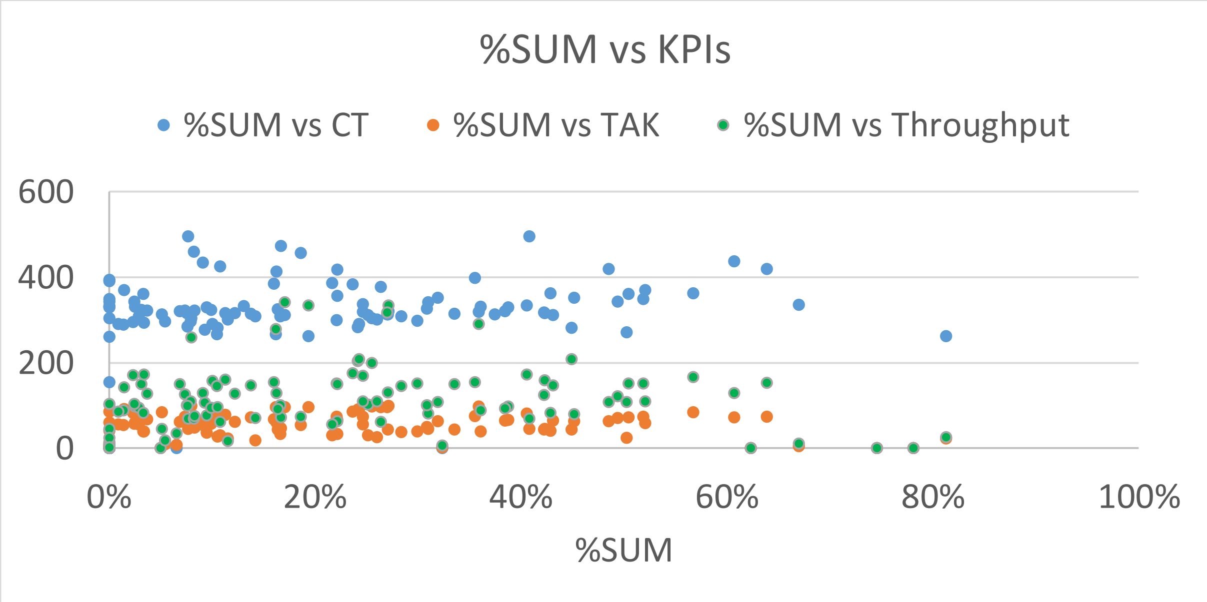


Plot 2. Scatterplot of the percentage the machine is the sole bottleneck against four KPIs, grouped per article. No significant correlations could be found between them.

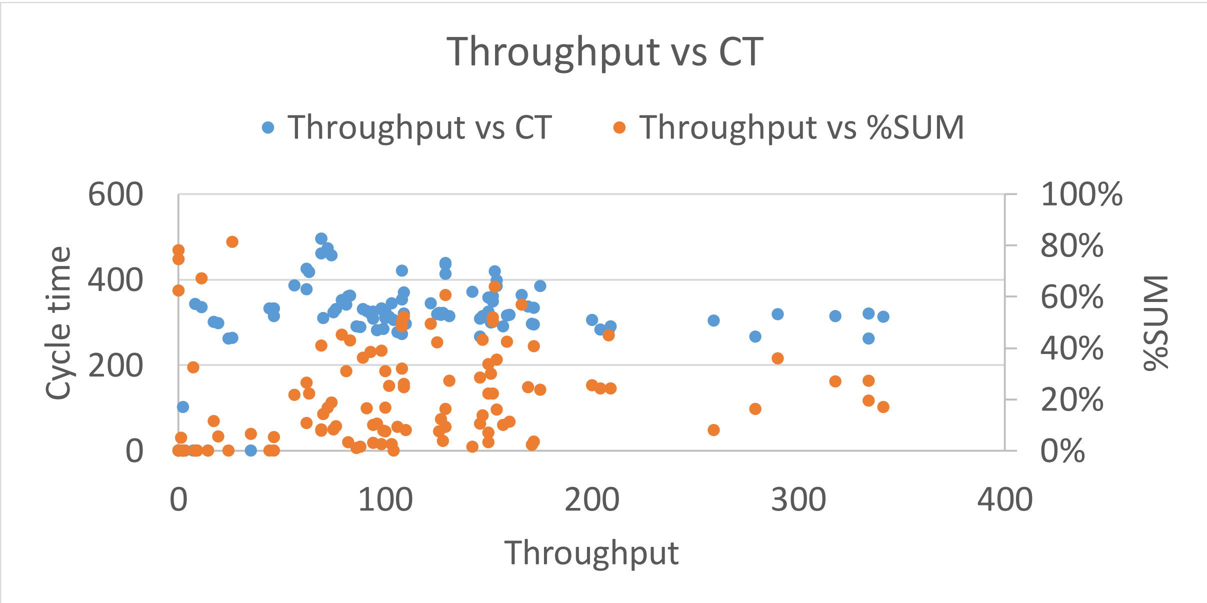
The correlation between the various figures have also been checked with scatterplots to make sure that the results are plausible. Plot 3 shows a scatterplot of some KPIs against the percentage of time the machine is the sole bottleneck, grouped per article. It is clear by the plot that there is no significant relationship between them. This is also true when adjusted per day, as seen in plot 4 to 6 below.



Plot 3. Correlation between a machines ITV and the percentage it is the sole bottleneck and sum of sole and shifting bottleneck respectively. No significant correlation could be found.



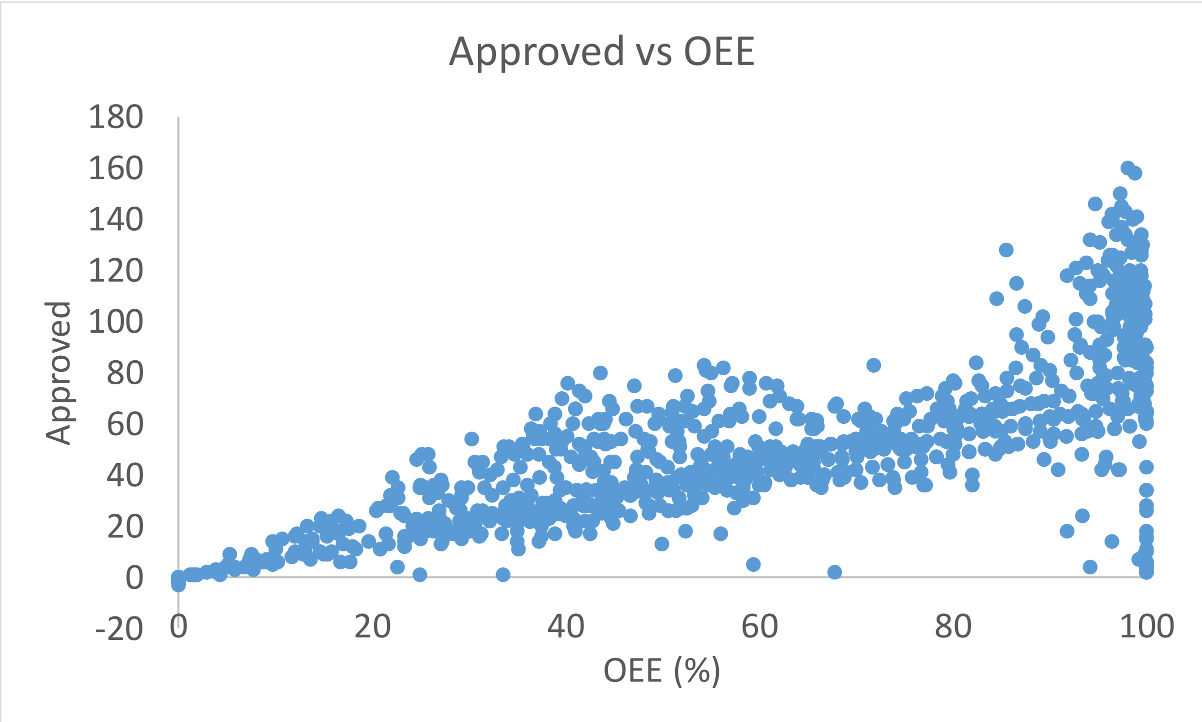
Plot 4. A scatterplot of the percentages the machine is sole or shifting bottleneck (x-axis) against three KPIs. No significant correlation could be found. The scale on the y-axis varies with the KPI analyzed, with seconds (CT), units (throughput) and percentage (OEE).



Plot 5. A scatterplot of the throughput vs the cycle time (primary axis) and the throughput vs the percentages which the machine is sole and shifting bottleneck (secondary axis). No significant correlation could be found.

	ITV	%SUM	Throughp.	OEE	Av. prod/h	Availability	CT
ITV	1,00						
%SUM	-0,10	1,00					
Throughput	0,30	0,04	1,00				
OEE	0,36	-0,03	0,74	1,00			
Average prod/h	0,09	0,22	0,30	-0,11	1,00		
Availability	0,21	-0,27	0,35	0,72	-0,64	1,00	
CT	0,12	0,15	0,05	0,28	-0,39	0,48	1,00

Table 9. The respective correlation among the different bottleneck indexes and the KPIs. For clarity, the correlations above 0.5 and below -0.5 is marked with green and red respectively. A more extensive table can be seen in appendix B.



Plot 6. A scatterplot of the number of approved products (y-axis) against the OEE (x-axis). The correlation among the two KPIs is 85%.

Between the KPIs there are some correlation. OEE and availability have a relationship as availability is one of the figures used to calculate the OEE. In one of the data set there have also been an 85% correlation between the throughput and the OEE. However, due to the problems of using throughput in a serial line explained in chapter 5.3, and the fact that it has been considered not useful for the model this have not been elaborated on further.

6.4 Recommendations

During the project, various insights in the data collection methodology have been acquired including how to improve them. Below follows a summary of the things that could be improved, and more importantly considered when implementing another similar system in the future.

- **Start looking at bottlenecks beyond cycle time.** It is obvious from this report that the machine with the highest cycle time is not necessarily the bottleneck. Ongoing research at the engine block manufacturing at Scania have for instance showed that the bottleneck is only the same as previous day 20% at the time, even if the line is still producing the same product with the same cycle times. Independently of the method used, an important step is to start using another method for finding the bottleneck than cycle time and have a standardized way of working with it once it is found.

- **Use active period % or bottleneck walk.** One of the key findings is that simply looking at the cycle times can give a misleading answer to which resource is the bottleneck. From a practical standpoint, the active period percentage or the bottleneck walk is recommended to use depending on the data collection at the particular line. Bottleneck walk is good as it does not require any automatic data collection at all, and gives the momentary bottleneck. For the lines with a good data collection system in place the active period percentage could be an easy and intuitive way of also adding the disruptions to the analysis, but it should be noted that it gives the average bottleneck over a period of time.

- **Focus on process variation as well as the absolute values.** As shown in this paper, the process variation is extensive with cycle times alone varying with over 10 percent and a big difference in disruption time among machines. With this in mind, the focus should first and foremost be to create a steady state. It is said that "engineers spend their whole education calculating steady state and normalities, and their whole careers trying to fight deviations". That is, while setting up the system perfectly is important the most important job for the engineers and operators should be to fight operators and make sure that it is working as intended.

- **Investigate the reason for varying cycle times**. This is not only a problem to consider for the data collection but for the production as a whole. For the type of numerically controlled machines that the line contains of, the cycle time should not differ significantly between work cycles. Yet, many instances where it differs by 10% could be found. Whether or not this is due to variations in the process or faults in the implementation of the data collection systems its root cause should be investigated.

- **Blocked or starved.** The MES system with its current implementation does not differentiate between the machine being blocked or starved, only if it is waiting. By separating if it is blocked because it does not get a new part or because it cannot unload its current, the arrow method can easily give the bottleneck (Li and Meerkov, 2009).

- **Historical data for more than one month.** Of course there have to be a trade-off between the cost of storing data and the usefulness of extended data, but in order to make deeper analyses previous data should at least be acquirable upon request.

- **Real time management** is an important part of the Scania production system. However, some of the data (for instance the cycle times) does not get into RS production until the next day which is a bit like trying to drive your car by looking in the rear-view mirror only.

- **Automate the bottleneck detection in the MES system.** There are computer programs and systems that can find the bottleneck (or the most likely bottleneck) automatically and present it clearly for the user. While this might not give a correct answer all of the times, it can act as a guideline. And all the methods presented in this thesis could easily be implemented into the MES system.

- **Prioritization order of gantry.** Already implemented in the controller for the gantry is the ability for the gantry to prioritize certain machines for any given article. That is, given that two machines are calling for the gantry at the same time it can prioritize one of them with the aim of reducing that machines waiting time. According to Goldratt and Cox (1993) one of the most important task is to make sure that the bottleneck is utilized at its fullest by making sure that the waiting time is minimized. Today, the function for prioritization is only very seldom used by the operators and the decision of which machine to prioritize is only based on “gut-feeling”.

7 Discussion

In this chapter the methods and results are discussed and elaborated further.

7.1 Method and results discussion

The objective of the thesis was to enhance the understanding of bottlenecks in a manufacturing line. This was done by finding the bottleneck using various methods and comparing the results, analysing the reasons that the machine became a bottleneck as well as investigating if there is a correlation between the machines likeliness of being a bottleneck and its key performance indicators (KPIs).

When comparing the different methods for finding the bottleneck it can be noted that they fail to identify the same machine as the bottleneck as well as ranking them independently of the timeframe when applied on data from a real-life production system. There can be many reasons for this, but when investigating the actual performance of the line it was apparent that some of the machines had a much higher ratio of disruptions compared to the other ones and that this changed on a day-to-day basis. As there is no right answer to which machine is the bottleneck it is impossible to determine which is the best at dealing with these situations. Although some of the methods claim to work independently of the timespan they are all based on probability theory and hence do need a certain sample size in order to work. The confidence intervals should account for this, but even when taking this into account they still point out different machines as the bottleneck.

This was an interesting finding that points out the importance of conducting more research using real-life data and not only simulation. Most of the methods claim to find the bottleneck with a high accuracy and are proven to do so mainly in a simulation environment, but as they point out different bottlenecks based on the same data it is obvious that at least some of them lacks accuracy in the environment and conditions investigated in this thesis. Hence, more real-life tests are needed to prove the methods and try to explain the reason of the difference in results.

No clear patterns regarding why a machine becomes a bottleneck could be distinguished. The ratio between the machine being up and running and down due to some disruptions such as breakdown or setup is varying extensively between the various days and articles. Hence, the machines could be bottlenecks both because they lacked in capacity or because they could not be used to their full capacity due to disruptions.

As the name suggests, the Key Performance Indicators should give a good idea of a machine's performance. There are many reasons a machine could be the bottleneck. It could be due to a high number of disturbances, a long processing time or most likely a combination of them both. Either a machine is the bottleneck because it’s not running, or because it’s running too slowly. And as the KPIs are designed to measure this, there should obviously be a strong correlation where the bottleneck machine is clearly distinguishable in the KPIs.

Although looking at the OEE, MTBF, MTTR and cycle time respectively gives a good indication of what machine is the least functioning, the hardest to repair or the slowest process when it is indeed working there is no simple way of weighing them together to find which is actually the machine with the largest impact of system performance.

The results however clearly show that this is not the case. Although using accepted methods for finding the bottleneck and industry standard KPIs, there is virtually no correlation between them.

That is, given the values of the KPIs there is no simple way of determining which machine is the bottleneck of the system.

There are of course many possible reasons for this. It cannot be excluded that the implemented bottleneck detection methods, KPIs or correlation analyses are not performed properly. The data quality can be too lacking to make any useful results, either because of faults in the collection or due to extraordinary circumstances in the production not captured by the researcher. As indicated before, most of the methods are to this date are mainly developed and evaluated in a controlled simulation environment rather than in real life production.

An obvious objection about some of the bottleneck methods for doing such an analysis is that they tend to be very binary in pointing out the bottleneck. That is, at any given time instance the machine is or is not the bottleneck (Roser, 2001). They usually don't specify by how much the machine is bottleneck. That is if it has hundred times the cycle time of the other machines or if it is a difference by fractions of a percent. Over a period of time the methods give the time a machine has been or have not been the most likely bottleneck, and even though it can be statistically argued that the machine which is most often the bottleneck also has the biggest impact of the system this is not necessarily the case.

The KPIs however are more linear to their nature. In fact, linearity is the sole definition of a good KPI. And therefore, there might not be an obvious correlation between the absolute values in the sense that you can predict one of them given the other. But the fact that no clear trends at all were visible was indeed a result that was really unexpected.

During the project, it has become obvious that a clear strategy for bottleneck management is important. All of the machines have waiting times and no focused efforts are made at shorten them on the bottleneck. It is also clear that the bottleneck is indeed shifting even within one batch meaning that a structured approach is important in finding the bottleneck. Also what machine is the most frequent bottleneck is important in order to prioritize the maintenance and improvements activities where they yield the biggest improvement on the system.

7.2 Future research opportunities

While this project has been very focused on the bottleneck at one particular line, the question of how to find what line or department at the company that is the bottleneck is left untouched. This is of course as important, as the improvements should be directed to this very resource.

The different bottleneck methods failed to point out the same bottleneck in the serial line to which they were applied independently of the timeframe. To the authors knowledge, no other comparison of the methods on real-life production data have been made. It would therefore be interesting to compare the methods on another data set to see if they still fail to point out the same bottleneck as well as a deeper analysis to why this is the case.

Because the project could not find any correlation between the KPIs and the machines likeliness of being a bottleneck, this is still an opportunity. By using other data or another approach for the correlation analysis, another result could possibly be achieved.

8 Conclusion

Knowing which resource that is the bottleneck is important in order to improve, as every improvement on a non-bottleneck is nothing but a mirage. Finding them however is not trivial and there are various methods and techniques to do so, each with their benefits and drawbacks. In this thesis, some of the most frequently used bottleneck detection methods are applied and compared in a case study at SCANIA CV in Södertälje.

The line was analysed during a 30-day period and the bottlenecks were analysed for the whole period, on a day-to-day basis as well as per article using different bottleneck methods such as shifting bottleneck, average active period and the percentage of time the machine was active. The results show that the bottleneck is shifting between the days as well as during an article meaning that the theoretical capacities of the machines does not fully explain which machine is the bottleneck but disruptions and abnormalities have to be considered as well. The various methods also fails at pointing out the same bottlenecks or rank them in the same order of likeliness independently of the timeframe studied.

Furthermore, the relationship between the machines likeliness of being a bottleneck and its key performance indicators (KPIs) was investigated to see if it is possible to find the bottleneck solely by looking at them.

To test the hypothesis, a serial line containing of four machines and one gantry was selected and the data was collected using the MES system RS production by Good Solution. The data was then analysed and the bottleneck calculated with the shifting bottleneck and the active period method for the whole period as well as on a per day and per article basis. A correlation analysis was carried out to see the relationship between the KPIs and the bottleneck indicators.

Q1: What are the main reasons that a machine in an automatic serial manufacturing line becomes a bottleneck?

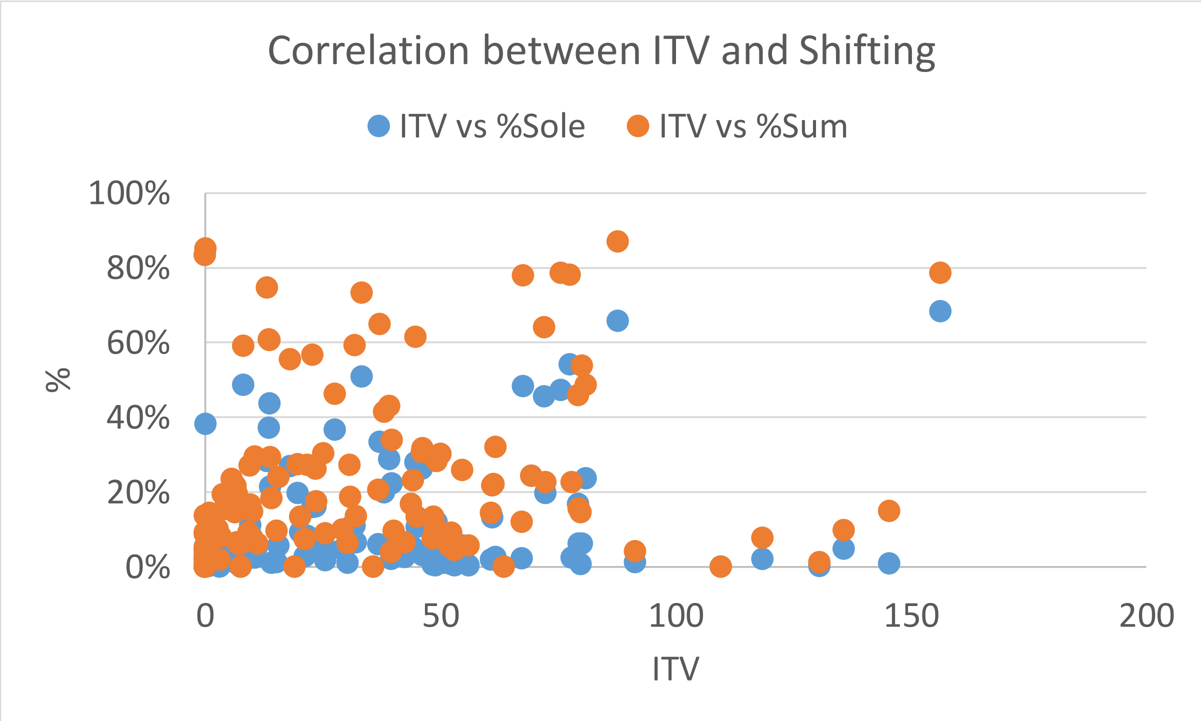
It is difficult to tell why a machine becomes a bottleneck. This thesis shows that even within a batch, that is for the same product that should have the same cycle time the bottleneck shifts between the machines in the line indicating that the disruptions play a big role.

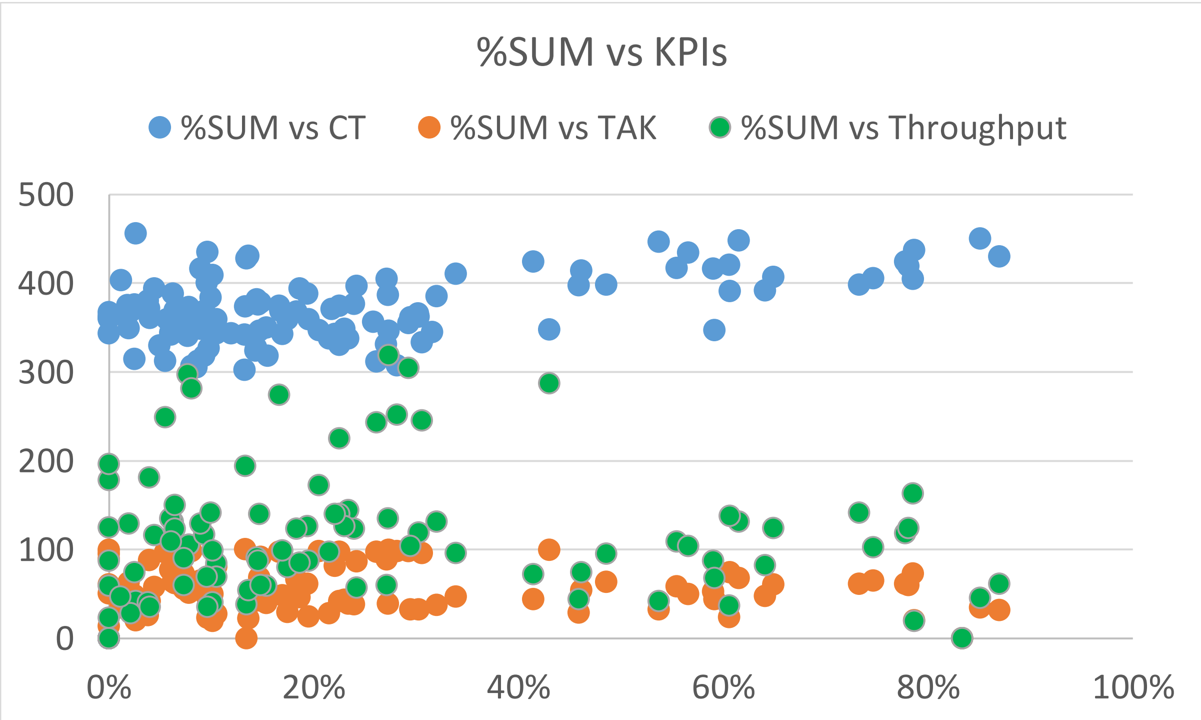
Q2: What is the relation between the machines likeliness of being the BN and its KPIs?

The results clearly show that there is no significant correlation between the bottleneck indicators and the KPIs. Hence, no way of finding the bottleneck through KPIs could be found.

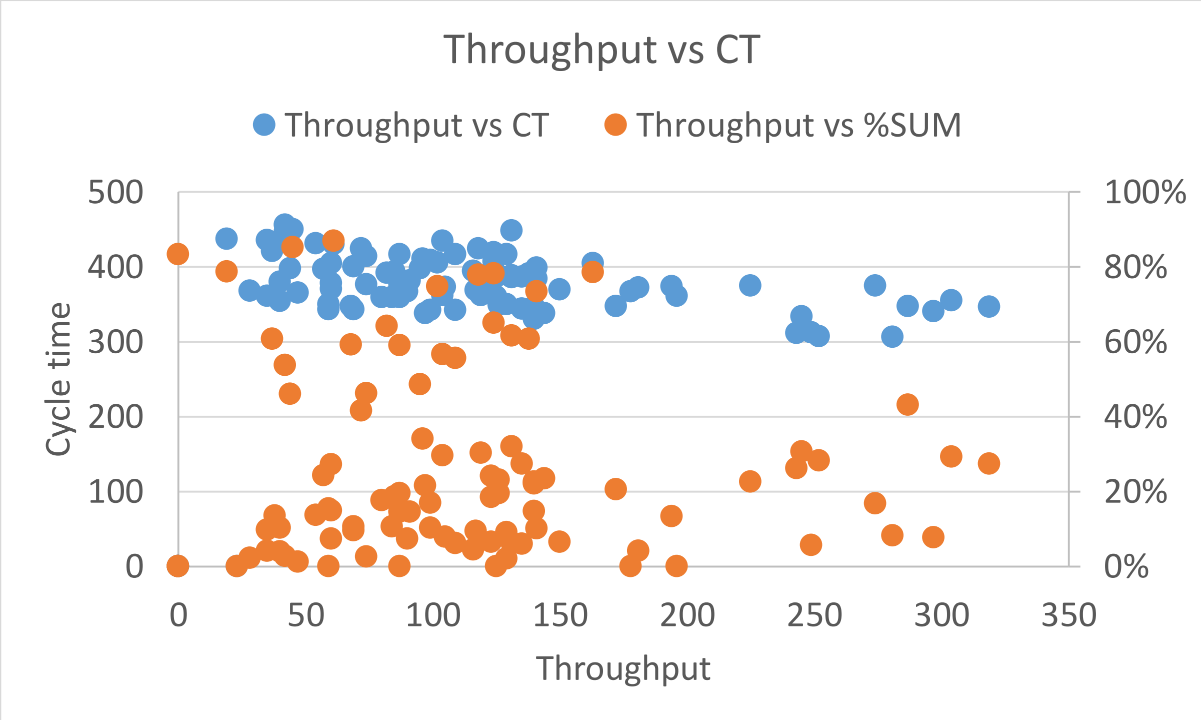
9 Appendix

Appendix A: Scatterplots correlation for line number two





Explanation of abbreviations: %SUM = percentage of time the machine is sole or shifting BN according to the shifting BN method. ITV = Inter-departure time. CT = Cycle time. TAK = OEE.



Throughput vs CT
Throughput vs CT
Throughput vs %SUM
Cycle time
500
400
300
200
100
0
100%
80%
60%
40%
20%
0%
0
50
100
150
200
250
300
350
Throughput

Appendix B: Extended correlation matrix

In this appendix a more complete correlation matrix is presented.

	Av CT inkl stop	CT	Availability	Average prod/h	TAK	Throughp	%SUM	%Shift	%Sole	Date	#	Shift BN	Sole BN	ITV
ITV	-0,17	0,12	0,21	0,09	0,36	0,30	-0,10	-0,10	-0,05	0,23	0,07	-0,10	-0,05	1,00
Sole BN	0,01	0,03	-0,26	0,22	-0,04	-0,04	0,83	0,19	1,00	0,17	0,28	0,19	1,00	
Shift BN	-0,14	0,23	-0,15	0,10	0,01	0,11	0,70	1,00	0,19	-0,14	0,47	1,00		
#	-0,08	0,14	-0,09	0,16	0,10	0,31	0,47	0,47	0,28	-0,09	1,00			
Date	0,11	-0,45	-0,17	0,28	0,04	0,19	0,05	-0,14	0,17	1,00				
%Sole	0,01	0,03	-0,26	0,22	-0,04	-0,04	0,83	0,19	1,00					
%Shift	-0,14	0,23	-0,15	0,10	0,01	0,11	0,70	1,00						
%SUM	-0,08	0,15	-0,27	0,22	-0,03	0,04	1,00							
Throughput	-0,28	0,05	0,35	0,30	0,74	1,00								
TAK	-0,35	0,28	0,72	-0,11	1,00									
Average prod/h	-0,11	-0,39	-0,64	1,00										
Availability	-0,36	0,48	1,00											
CT	-0,50	1,00												
Average CT incl stop	1,00													

Appendix C: Bottleneck figures per machine and article

Data set 1

In this appendix are the summary table for the time in seconds each machine has been sole and shifting bottleneck respectively for two data samples of size 30 days taken from the same line. The articles that have been produced more than one time during the period is shadowed in the same colour for clarity.

	Milling Sole	Milling Shift	Marking Sole	Marking Shift	Gantry Sole	Gantry Shift	Turning Sole	Turning Shift
Article 1	7468	3837	0	0	579	3839	0	0
Article 2	22488	8225	2373	4142	888	1606	2658	8312
Article 3	8694	11384	1091	6354	8251	2882	1916	10773
Article 4	39576	24459	490	10812	9435	12182	7696	18621
Article 5	11508	54261	49	2664	8537	5276	5886	26600
Article 6	9474	12066	0	0	668	1455	3956	6783
Article 7	34214	33204	4324	23790	18596	5900	22515	29450
Article 8	12152	15743	222	7644	9371	31	6520	5890
Article 9	14536	15229	1086	12885	3716	3006	6716	11982
Article 10	13776	17010	67	7043	5465	10891	2256	13828
Article 11	6760	7107	0	2459	2252	2520	3610	4696
Article 12	17801	15838	199	6183	335	45	19234	14819
Article 8	33343	11924	314	460	1040	9057	549	3057
Article 13	6490	19008	219	6301	5245	9355	1734	22891
Article 1	8397	8872	30	3213	338	3404	15	8588
Article 2	5838	4467	0	0	0	2	4736	6565
Article 14	6185	13621	119	11315	7207	5850	17543	15490
Article 3	203212	27492	4	3389	7420	13690	11609	10841
Article 14	11635	21220	87	8057	10280	16499	89181	25016
Article 15	78401	14295	83	5871	18665	13500	11070	24810
Article 14	10835	5440	0	2869	4794	2195	633	1031
Article 16	13852	8691	49	1950	521	7840	855	2024

Data set 2

	Milling Sole	Milling Shift	Marking Sole	Marking Shift	Gantry Sole	Gantry Shift	Turning Sole	Turning Shift
Article 15	20416	8738	73	3651	1520	2218	97	7366
Article 14	10836	5439	0	2869	4794	2194	633	1031
Article 16	17960	4584	49	1950	281	3408	856	2024
Article 8	18939	36336	114	8149	6288	9268	4570	31494
Article 10	15221	13859	58	2312	14675	2082	8195	11339
Article 7	8615	23538	4639	6480	2353	9886	21037	28589
Article 8	21531	15034	955	7325	27591	6352	5822	17079
Article 12	11517	8710	18	7261	2399	28960	41115	38841
Article 9	12292	15366	114	7556	782	7110	12832	13867
Article 13	34414	65151	3426	11284	3473	4447	5807	48653
Article 14	5974	13632	46	3398	9962	6301	2163	9840
Article 15	3991	23988	3391	11658	1111	506	5631	13577
Article 17	27901	16705	2492	4741	1571	6845	10854	13233
Article 7	25169	19740	914	4607	3242	2286	5127	16076
Article 12	12194	17180	692	6038	455	5863	6958	21794
Article 8	10958	29036	118	13143	4082	5905	8281	22931
Article 14	4894	15756	0	3400	30319	5176	1838	14478
Article 18	13039	28636	684	5609	1714	5507	12242	22398
Article 12	14980	16601	36	6867	2086	8553	3926	21477
Article 8	11483	21935	461	5346	2257	4028	3773	24604
Article 15	19535	25445	702	6227	2017	3966	5483	12764
Article 19	16979	6339	22	1351	439	1448	2110	2955
Article 11	9386	5419	456	2578	3182	1071	3422	3944
Article 3	5466	10101	60	4980	2361	9983	3872	10399
Article 20	21967	12409	443	4209	1712	2721	13948	15110
Article 21	24405	12451	0	2822	1299	2081	8105	13634

Article 22	17869	14949	0	645	2416	7271	5481	6102
Article 23	12249	16621	25	5686	4731	350	5217	14705
Article 1	18578	16826	0	1736	1243	5344	849	11814
Article 2	17538	16195	1678	14888	1781	6297	89	15020

Comparison of bottleneck same article between runs set 2

In this appendix a summary of the bottleneck machine during each run for the articles that are produced more than one time during the 30 day period is presented.

	Run 1	Run 2	Run 3	Run 4
Article 15	Milling	Milling/marking/Turning	Milling	N/A
Article 14	Milling	Milling	Milling	N/A
Article 8	Milling	Milling	Milling/Turning	Milling
Article 7	Turning	Milling	N/A	N/A
Article 12	Turning	Milling/Turning	Milling/Turning	N/A

	Run 1	Run 2	Run 3
Article 1	Milling	Milling	N/A
Article 2	Milling	Milling/Turning	N/A
Article 3	Milling/Gantry	Milling	N/A
Article 8	Milling	Milling	N/A
Article 14	Turning	Turning	Milling

Appendix D: Pseudo-code of script

A, B, C, D, E matrices of dimension #machines x #seconds of analysis.

cycleTimes - the exported cycletimes.

disr - the exported disruptions.

machineIndex - the row the specific machine has in the matrix.

startTime - the number of elapsed seconds since the start of measurement.

```
For Each row in cycleTimes
        For i = 1 To CycleTime
A(machineIndex, startTime + 1) = 1
Next i
Next
```

```
For Each row in disruptionTimes
        For i = startTime To endTime
                A(machineIndex, i) = 1
        Next i
Next
```

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