How can discrete event simulation contribute to increased output?

A case study about improving a production line at Veoneer using discrete event simulation

Master's thesis in Quality and Operations Management

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Abstract

Veoneer, a large subcontractor to the automotive industry, has seen an increased demand for its products. To match this demand, the company must have enough production capacity. This case study has collected data using a qualitative approach to replicate the actual production line and perform a discrete event simulation (DES). The simulations were used to investigate if there are potential improvements that could be made to increase the efficiency of the production line.

In total, 220 simulations with five different improvements were tried. Furthermore, the simulation also evaluated other simulation variable effects, such as mean time to detect (MTTD) or the number of work-in-progress. The project found results indicating that reducing the MTTD could significantly affect the overall output. Additionally, two other improvements seemed to affect the production line positively by either expanding the capacity on the identified bottleneck or subordinating the rest of the system to that particular station.

Keywords: Discrete event simulation, manufacturing, SMT, circuit boards, MTTD, Mean time to detection

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Table of Content

List of figures

List of tables

1. Introduction

This chapter elaborates on the background and the problem description of the study. Furthermore, it states the aim and questions researched in the report. Lastly, the delimitations are declared.

1.1 Background

Over time, the production of manufactured goods has become more and more centred around automated machines and robots due to the push toward lower throughput times and lowered costs (Westrom, 2022). This development has led to a higher degree of complex products being produced due to the improved accuracy of the machines.

The western countries lose more and more production to low-cost countries in the east, where the competition has increased (Alexander, 2021). The competition drives the demand for technological superiority to ensure high competitiveness and to be able to compete with a low-cost product. One tool suitable for technological superiority is discrete event simulations, which can contribute to the optimisation of companies' ability to convert the input to output (Pehrsson et al., 2016).

The report is written at Veoneer, a sizable Swedish subcontractor in the automotive industry, as a pilot study to evaluate the effectiveness of using discrete event simulations to improve production. The study will focus on one of the production lines, SMT-006, creating circuit boards which are a sub-component of the finished products being sold. The study aims to assess how different simulation variables, defined as every type of input to the simulation model, and potential improvements affect the overall production output. Effective improvements could lead to lower throughput times and lower costs, enabling a higher degree of competitiveness. The study also aims to examine hidden problems that can not be evaluated through traditional mapping of the production line by doing manual calculations in Microsoft Excel.

Veoneer's products are niched towards safety and protection, such as camera sensors at the front of automotive vehicles and radar systems around the vehicles. Since it is a matter of safety, it is vital to ensure that all variants of products are functioning correctly as they are intended to handle the driver's safety. The products are complex and therefore require machines with high precision in manufacturing to ensure the quality of the product.

The SMT-006 is one of nine fully automated production lines and is the first operation in the assembly of the products. Despite the degree of automation, operators have to perform some manual work. The production line deals with surface mounting on circuit boards, adding components on either one side or both sides. The circuit boards are thereafter transported to operations downstream through kanban systems, which are used as sub-components to the finished products.

The layout of the SMT-006 line has a high degree of dynamic complexity. Holweig et al. (2018) state that dynamic complexity is a high degree of interaction between a production's static components. Since the process needs to work on both the upside and downside of the circuit board, the layout configuration adds dynamic complexity to the flow of the products. In addition, variations in cycle times from the machines, depending on which side of the circuit board is being processed, increase dynamic complexity for the overall production. Other factors contributing to an increased complexity are the number of products in production and the variety in breakdowns of machines.

Haji Ali Afzali & Karnon (2014) states that discrete event simulations are appropriate for complex situations, such as major production systems. For example, a common tool to better understand how input and transformation variables affect the overall output is a discrete event simulation to map the production line to a virtual simulation (Pehrsson et al., 2016). It could also act as a base for answering how potential improvements influence the flow and output of the line.

1.2 Problem Description

Expanding on the Background, another factor adding to the dynamic complexity is the loop created by the need to process the circuit boards on both sides. Figure 5 in the Current state chapter showcases the current production line. After first being processed on the top side, the circuit boards loop back to the same machines to be processed on the bottom side. Engineers at Veoneer have previously tried to manually develop improvements to the production line without success due to its high complexity. By experimenting with improvements directly on the production line, a significant risk of disturbing the actual production is enhanced, affecting overall costs and productivity. Another downside to not using discrete event simulations is the lack of identifying second-order effects that can occur, such as impacts on improving one station and the effect this has on the rest of the production line. The second-order effect further increases the complexity of trying to improve the production line without DES. The alternative to DES is to use an analytical tool such as Microsoft Excel. However, the problem with using excel is that it can not evaluate the dynamic effects that occur with the variety of different variables.

Chung (2004) mentions several key benefits of using simulations. These benefits are, for example, gaining greater insight into the operations, it helps develop new operating policies to increase performance, it helps with testing new improvements before implementation, and gaining information without disturbing the actual production. The simulation also contributes to experimentations in compressed time, reduces analytic requirements and can act as a tool for easily demonstrated models.

Based on the complexity of the production, discrete event simulations could be used as a tool to determine the effects on the flow from potential improvement solutions. Furthermore, it could also help determine the effects of configuring some of the simulation variables.

1.3 Aim

The production of circuit boards is complex in many aspects, such as how individual changes impact overall production, with the risk of so-called sub-optimisation. Creating a simulation with representative data from the actual production makes it possible to more easily determine the overall impact each simulation variable and individual changes have on the production output. Production output is measured by production time for a fixed amount of products.

To determine what changes that could improve the output most significantly, it is essential to identify where in the production line the need for improvement lies. By using a discrete event simulation, the data from the production line can be visualised to make it easier to identify potential bottlenecks, how suggested improvements alter the production, and understand how other various inputs affect the process and flow of products. Therefore, the project aims to enable a more simple solution for understanding how different simulation variables affect the production line's output.

1.4 Research questions

The scope of the project is compiled in the following two questions.

- What simulation variables have the greatest effect on the overall production output?
- What improvements have the greatest effect on the overall production output?

1.5 Delimitations

One of the benefits of the discrete event simulation is seeing the overview of the system as a whole, such as an entire factory or production line. This report will only focus on the production of circuit boards and is limited to one production line out of nine. Even though the production lines work on the same products and are pretty similar, they differ in the sense of other types of machines with different types of capacities. Therefore improvements to the production line in this project will most certainly affect other lines differently due to slight differences in production layout and different cycle times for similar machines.

The project is limited to only simulating the effects of one product due to the high amount of data gathering required for each product. The simulated product was chosen by Veoneer. In addition, the potential improvements are limited to plausible incremental upgrades rather than more extensive drastic changes such as significant changes in the layout design.

2. Theoretical framework

This section will cover topics regarding the traditional manufacturing industry, such as process theory, continuous flow, lean management, and describing areas of discrete event simulation.

2.1 4 V

Companies' operations have a mission to reach the customers' expectations and satisfy their needs. However, all customers do not always have the exact needs, and companies can therefore position themselves to target a specific segment (Slack & Lewis, 2020). In order to target a specific customer group, the company's internal operations need to be in line with the chosen strategy, where differentiation is made from the following four variables, Volume, Variety, Variation, and Visibility. Examples of opposites will be discussed, yet, most operations are usually positioned somewhere between.

Volume is the relative number of output the processes give where high volumes suit a high degree of repeatability. Thus, having a high degree of specialisation in the equipment is both feasible and economically preferable (Slack & Lewis, 2020). These specialised machines and technologies enable increased efficiency. At the other end of the scale is low volume, where the standardisation of the process is much lower. Staff performs a broader range of tasks and is less open to systematisation.

Variety determines how many different types of products the operations can offer. To produce a high degree of variety of products, a wide range of different activities must be performed, and a wide range of skills and technology is needed. The higher the variety, the higher the costs, is a general rule (Slack & Lewis, 2020).

Variation is the fluctuations in demand in terms of quantity rather than the wide range of products as in variety. With a low variation, it is possible to plan all activities in the production. In contrast, high variation means the resources and production have to be continuously adjusted to fit the demand. In some cases, there is a need to have an increased capacity to adjust for seasonal or extraordinary effects (Slack & Lewis, 2020).

Visibility is the amount of insights the customer has into the value being created. Generally, the operations that work directly with the customer and have some sort of service in their offer have higher visibility than, for example, a manufacturer that never interacts with their customers other than in the purchase phase (Slack & Lewis, 2020).

2.2 Process

A process can be defined as creating an output from certain inputs combined with some sort of transformation. The input can be raw materials and components. The transformation happens through machines, workers and manufacturing methods that transform the input to create a specific output. Finally, the output is what gets out of the process. As Bergman and Klefsjö (2012) puts it:

> A process is a network of activities that repeats itself and aims to create value for an external or internal customer. (p. 457)

There are mainly three types of processes, main processes, support processes, and management processes (Bergman & Klefsjö, 2012). The main process aims to meet the external customers' needs and transform the company's resources into the company's main offer. It can be processes such as production processes or logistics processes. Furthermore, the support process aims to meet the internal customers' needs and support the main processes. Finally, the third type of process, the management process, aims to decide about the company's direction and develop strategies to help the company go in the decided direction.

Processes can have many different shapes and purposes depending on the branch or type of process. All of them have different characteristics regarding, for example, flexibility, standardisation, and predictability and are appropriate for different settings (Bergman & Klefsjö, 2012). For example, in a main process with continuous flow, the characteristics are high volumes with low flexibilities, high standardisation, and high predictability.

2.3 Continuous Flow

The continuous flow process is a highly automated process which makes it efficient when running at full capacity. It has a high degree of output which creates a low unit cost. However, the process has a low degree of flexibility and is weak to changes in its variables. A common perception about mass production is that it brings two benefits (Liker, 2009). The first is production of scale. The overall idea is that the machines will produce such a large quantity that set-up times will be kept to a minimum, and have the machines work continuously. The second benefit is visibly effective work schedules where the administrative load is kept to a minimum.

When designing a process, the overall goal is to achieve an efficient output for the products produced. An advantage to achieving an efficient output is to have a constant flow through the whole process and have the production system as balanced as possible. With a continuous flow, there is a large number of work-in-progress, which are not finished products currently in production. Often the overall goal is to produce as large a quantity of products as possible but reduce the number of products in work. According to Liker (2009), a drawback with much work in progress is the aspect of defective units. If a production system malfunctions and produces defective units, it might take time to notice the error. With many units in production, there might be many units that need to be discarded due to the error before the fault is discovered. Another aspect is the increase of tied-up capital with many products in work. The tied-up capital can affect the business's profitability (Jonsson & Mattsson, 2016).

2.4 Operations Management

The core of operations management is to design, measure and improve processes. One of the common things to improve is productivity. Productivity can be defined as having the performance of the process to be as good as possible with the least amount of input and to reach the highest amount of output (Bellgran & Säfsten, 2010). It is expressed as a percentage and results from the equation below.

$$\frac{Output}{Input} = Productivity$$

Productivity can also be described as the percentage of value adding time (t_{va}) to the total amount of time (t_{tot}). Advantages to calculating productivity using time includes easy comparisons between plants, ease of measuring, and ease of understanding.

$$\frac{t_{va}}{t_{tot}} * 100 = Productivity$$

Since the output and input are quantifiable, the productivity is measurable. This is a fundamental condition for improvement. Holweg et al. (2018) argue that variation of what is coming off the production line can be expanded by increasing productivity. Variety exists in every type of process through differences in inputs, tasks and output (Holweg et al., 2018). It comes in the form of quality, quantity, and timing variation.

2.4.1 Key Performance objectives

According to Slack & Lewis (2017), there are five key performance objectives for measuring an operations performance. The first is quality. Quality aspects can be divided into conformance quality and customer experience quality. Conformance quality is design standards set by the producer, while the purchaser determines customer experience quality. For a manufacturing firm that makes physical products, conformance quality can be to produce products to the predefined specification, both persistently and reliably. Customer quality is a soft aspect regarding quality and could include the degree of helpfulness and courtesy in service-based operations (Slack & Lewis, 2017). The second performance objective is speed. The speed can also be measured in multiple ways but can be seen as the time elapsed from the beginning of a process to the end. The third is dependability which means the ability to deliver on an agreed timeslot. Dependability is an aspect that focuses on delivering on time, not past or before the agreed-upon time. Fourth is flexibility which handles four areas of variety (Slack & Lewis, 2017). It is product flexibility which is the ability to produce new products or new versions of current products, mix flexibility which is the ability to change the offered product mix, volume flexibility which is the ability to adjust the output needed, and delivery flexibility which is the ability to adapt to changes in delivery dates. Lastly, the fifth performance objective is cost. This is an objective that measures the cost of producing the product.

2.5 Balanced processes

The aim of maximising a process's utilisation is to have them work without excess balancing losses. Balancing losses creates unwanted wastes and bottlenecks that disturb the flow of production (Holweg et al., 2018). Therefore, operations continuously need to remove these balancing losses and rebalance the production line.

2.5.1 Takt time

A good tool to achieve a balanced process is to use takt time. Liker (2009) argues that takt time is decided by the customer demand and available resources (time). Available time divided by the number of products in demand gets a takt time each station on the production line should aim to have. The overall idea is that all stations within a production system will have the same time to work and, in turn, create a smooth flow. Having one station produce faster than the takt time will lead to several wastes according to Lean management, such as overproduction and excess inventory (Liker, 2009). On the other hand, if a station produces slower than the takt time, it creates a bottleneck, and the producer may not meet customer demand. This may result in potentially losing the customer. Therefore, takt time and continuous flow are best suited for repetitive processes where the volumes are high and a certain stability in cycle time per unit (Liker, 2009).

2.5.2 Bottleneck

A bottleneck can be defined as the station in the production with the lowest capacity to manufacture the products (Holweg et al., 2018). The overall capacity will be bound to the throughput time of the slowest operation. For example, a production line can not produce a product every 20 seconds if one of the stations in the production has a cycle time above 20 seconds. Bottlenecks can be categorised as chronic bottlenecks and one-time occurrences. One-time occurrences can be machine breakdowns or material shortages (Holweg et al., 2018). Chronic bottlenecks are either stationary or floating. Identifying a stationary bottleneck is, in relative terms, straightforward. It is typically building a stack of work-in-progress before the bottleneck and has the slowest cycle time of all stations. To verify that the station is the bottleneck, the output should immediately increase when improving the bottleneck's capacity (Holweg et al., 2018). However, the floating bottleneck is more challenging to identify. Floating means that the bottlenecks move based on the production schedule or customer demand, both internal and external. It can vary depending on what type of product the process is producing or the mix of products scheduled to be produced.

2.5.3 Balancing Losses

The goal of a production line with a continuous flow is most often to have a balanced system with zero balancing losses (Holweg et al., 2018). However, this is in practice almost impossible to reach due to differences in throughput times of the different machines. Balancing losses is determined by the machine with the slowest cycle time, where the loss is the difference in time compared to every other machine. The balancing losses result in unwanted waiting times. To achieve a balanced production line, Holweg et al. (2018) state that it is needed to continuously seek and identify the bottlenecks and then break them. Slack et al. (2007) define balancing losses like this:

> Quantification of the lack of balance in a production line, defined as the percentage of time not used for productive purposes with the total time invested in making a product. (p. 211)

One common reason for balancing losses is breakdowns. Depending on the fault, these breakdowns can vary from a couple of seconds to many hours. Breakdowns that only last a couple of minutes or less are called micro stops (Trubaciute, 2020). Typically these micro stops are underestimated since the repair time is short, and the fault may not be anything severe. The short stops result in a higher challenge in gathering this type of data. Single micro stops do not contribute to a significant disruption to production individually if noticed without delay, but combined add up to a big chunk of cumulative downtime.

Creating buffers in a production system is a way to handle uncertainties such as potential supply shortages (Jonsson & Mattsson, 2016), yet there are some negative aspects. Liker (2009) points out that with an increase in buffers, work-in-progress increases. These products tie up capital that could be used for something more value-adding and increases the liability costs. However, Liker (2009) also states that even a world-class process needs some buffer to run smoothly, yet the goal is to keep them as small as possible. According to Jonsson & Mattsson (2016), the buffers can be a great tool to reduce balancing issues and strengthen connections between stations, especially in a line production layout. Buffers costs and benefits are a trade-off as a buffer can reduce revenue losses in the form of absent sales, fees for delivery delays etc.

2.5.4 Theory of constraints

A method to reach a more balanced system is Theory of Constraints. It is divided into the following five steps (Cox & Schleier, 2010):

1. The first is to identify the system constraint. This is the part of the system that is the weakest link. It is often displayed in physical clues such as the highest throughput time of a machine in an operation or fully stocked shelves before the bottleneck.
2. The second step is to decide how to exploit the system's constraints. According to Cox & Schleier, this step is to make sure that you get the most out of the bottleneck as possible. The bottleneck should with that logic always be used and not be a subject of different wastes such as waiting times and over-processing.
3. The third step is to subordinate everything else to the bottleneck. In this step the organisation makes sure that the rest of the process adapts to support the decisions taken in step two such as policy changes or a change of ways in how to operate the process (Cox & Schleier, 2010).
4. The fourth step is to elevate the constraints. This simply means increasing the capacity of the constraint and can be done in many different ways. For example, according to Anjoran (2021), it can be by adding resources in the form of workers and machines to increase the capacity.
5. Once the previous four steps are done, go back to step one.

By following these steps in theory of constraints improvements can be made for the entire production line. As Cox and Schleier (2010) put it:

> An hour lost on the bottleneck is an hour lost on the entire system; an hour gained on a non-bottleneck is a mirage. (p. 4)

2.6 Maintenance and Operating Data

Maintenance is performed to ensure the lifespan of all machines and is of importance to all operating processes (Bergman & Klefsjö, 2012). Not performed maintenance could contribute to loss of revenue due to unexpected downtime or failures. It also increases the opportunity cost as machines lose capacity during downtime.

Several key measurements are used for both maintenance and operations. One metric commonly used is downtime, which describes the amount of time a machine cannot create the output intended due to malfunctions or planned maintenance. Downtime can be described in absolute time and as a percentage of the total time (Aspentech, 2022). Another metric that describes the quality of an operation is the yield. Yield is a measurement that displays the overall quality of the produced products and is calculated by the following equation (Asprova, n.d). Correct or non-defective products are determined by the customer's specifications.

$$Yield = \frac{correctly\ produced\ products}{total\ produced\ products}$$

Mean time between events is a method for planning reliability calculations. It measures the time between different events where the machine is not operating. These events include failures of the machine, planned and unplanned maintenance, breaks, or other events where the machine is not used (Stamatis, 2010).

Mean time between failures, or MTBF, is a common measurement that states, on average, how long the machine is operating between failures or downtime (Stamatis, 2010). The measurement can be derived from the available running time divided by the number of breakdowns. See the equation below.

$$MTBF = \frac{total\ working\ time\ -\ total\ breakdown\ time}{\#\,of\ breakdowns}$$

Mean time to repair or MTTR measures the amount of time that, on average, is required to repair the machine or process when a breakdown has occurred. The measurement indicates the difficulty of repairing the machine (Stamatis, 2010). MTTR can be calculated by dividing total maintenance time by the number of repairs.

$$MTTR = \frac{total\ maintenance\ time}{\#\,of\ repairs}$$

Mean time to detect or MTTD measures the time to detect a fault occurring in the system (Sisense, 2020). This can be either the system or the worker's ability to detect the error. MTTD reflects how well the system is adapted to identify potential faults. Longer MTTD results in more extended downtimes and loss of revenue. MTTD affects the MTTR metric as the mean time to repair includes the detection time.

Another metric for evaluating an operation is to look at individual statistics of each machine. Common statistics include utilisation, blockage and starvation (Klaver, n.d). Utilisation, also known as busy rate, is the total time during production that the machine or process is used to transform a product. It is usually described as a percentage of the total time. Blockage, usually calculated in percentage, is the amount of time the operation cannot perform work due to a stoppage later in the production (Klaver, n.d). These stoppages can occur due to differences in throughput times as well as breakdowns. Starvation occurs when the operation or machine is functional but does not have any products to work on. This is usually due to breakdowns earlier in the production or differences in throughput time as the given operation or machine has to wait for previous machines to finish their work. Starvation is also described by a percentage of the total operating time.

2.7 Lean Management

Lean management is a way of thinking and working focused on maximising the customer value with as little waste and resources as possible (Lean Enterprise Institute, 2021). By auditing the organisation's processes and resources, it is possible to identify which functions create value for the customers and what is not. If it is not creating value, it should be removed.

In Lean management, eight types of waste are not value-adding and should be kept to a minimum (Liker, 2009). It is overproduction, waiting, unnecessary transports, over-processing the products, too much stock, unnecessary work steps, defective products, and unused creativity from the employees.

There are a lot of tools and principles originating from Lean management to help reach the objectives of keeping the waste to a minimum. One of them is the term "genchi genbutsu", which means "to go and see with your own eyes to really understand the situation" (Liker, 2009). By doing this, you are not taking anything for granted and can verify the data and information. Furthermore, seeing the situation with your own eyes opens up to really understanding the processes and problems. Once you understand the problems, then it is possible to solve the issue and continue to improve the company's processes (Liker, 2009).

Another thing that Lean management is putting weight into is the visual assistance to improve the operations. According to Liker (2009), a well designed visual system can improve productivity, reduce the number of errors and mistakes, help keep the lead times, improve the communication, and help keep the costs down. This is supported by Subramaniam et al. (2009), which say ergonomic signals such as auditory and visual aids help the operator respond quickly to things causing downtime and thus help the production line improve and maintain efficiency. Lee & Chan (2007) have found that using two different signals with both visual and auditory help improves the MTTD metric. There is, however, a potential drawdown. By having people frequently exposed to the signals, they can end up in a state of habitation where they pay less attention to them (Wilcox, 2011). It can be a setting such as a production line where they hear many signals from both their own machines and the neighbouring production lines' machines (Ocampo et al., 2012).

2.8 Discrete event simulation

To define Discrete Event Simulation (DES), clarification about each word is needed. First, discrete refers to a discrete distribution that can only take certain values with different probabilities connected to them (Statistics.com, 2022). An example of the probabilities can be the production of a machine, such as the probability of the machine producing ten products is 0.7. In contrast to discrete distribution, the continuous distribution can take any number in a specific interval that can be as big as infinity (Statistics.com, 2022). The next word, event, is, according to Johansson (2006), a happening at a single point in space-time. Lastly, the word simulation is the construction of an artificial object and its essential features with the intention of reproducing or imitating the happening (Johansson, 2006).

Mourtzis et al. (2014) state that changes occur at separate points in time in discrete simulations. Discrete simulations can have changes in either an event or time-driven way. The event-driven way determines when happenings occur with regard to the event itself and where time intervals are irregular (Moutrzis et al., 2014). However, the time-driven way determines happenings from the perspective of a particular passing of a specific amount of time. So the randomness of these happenings can be regarded as deterministic or stochastic.

Deterministic will always give the same output of every simulation as long as nothing of the input variables has changed (Moutrzis et al., 2014). On the other hand, stochastic is the opposite of deterministic since the simulations will not give the same output given that nothing has been changed with the input variables.

Simulations have been an excellent tool for making informed planning decisions, implementing, and operating the manufacturing set-up by, for example, finding bottlenecks or identifying layouts with optimal flows (Skoogh, Perera and Johansson, 2012; Li et al., 2009; Pehrsson et al., 2016; Roser et al., 2002). Traditionally, the simulations have been divided into two categories: one aims for long-term solutions such as designing layouts and the other to find more short-term optimisations such as operating and performance analysis (Haraszkó & Németh, 2015). According to Jahangirian et al. (2010), simulations within manufacturing have, during the last 60 years, developed to be a great and advanced tool to help improve a wide range of areas such as form different strategies, designs, training, and planning. Areas of use include manufacturing settings, business process simulations, logistics, transportation and distribution, and many more (Johansson, 2006).

Additional benefits of DES include understanding how the entire system works and is an excellent tool for identifying bottlenecks (Pegden et al., 1995). The DES tool can be used either as a strictly text-based simulation without visualisations or through photorealistic 3D based environments. This 3D environment will allow the simulators to see how different simulation variables affect the system and gain insights about the importance and interaction of these variables. Further, Pegden et al. (1995) argue that improvements to the system can be tested without committing relatively many resources. When doing these tests, it is also possible to compress the time and see what long term effects changes and variables can have.

However, there are some drawbacks to DES as well. For example, since the simulations are a string of random variables, it might be challenging to determine whether the output received results from the system's characteristics and interrelations or if it is the randomness that gives the result (Pegden et al., 1995). Another drawback is the amount of time and resources that need to be invested in the modelling phase of the simulation project. That is why it is essential to use the simulations for projects that are an appropriate size to make them efficient.

2.8.1 Visual Components

Visual Components is a 3D environment software that uses discrete event simulations for development of manufacturing solutions. The software enables manufacturers, engineers, and others to design and simulate both existing and new production lines. The software has pre-existing machines and conveyors from many large manufacturers and allows for importing CAD files. In addition, the simulations can be run at many different speeds depending on the hardware's processing power (Visual Components, 2022).

The primary tool for configuring each machine and production function was done by what Visual Components call Process Nodes. These process nodes have very high customizability. Each node or object in the software has a property and behaviour modelling configuration that allows for each preferred conditional to be added. These conditionals include, for example, boolean statements, signal handling, sensors, and dimensions. In addition, if some function does not exist, the software allows for manual programming through Python Scripts which further enhances the programming capabilities (Visual Components, 2022).

3. Circuit boards

A lot of modern electronic products have a circuit board. Even though there are usually many components in an electronic device, circuit boards are one of the most crucial. A circuit board is flat and rigid, consisting of insulating material (Keim, 2020), with electrical components on it (Bhunia & Tehranipoor, 2019). These components are, for example, resistors, capacitors, or inductors (Apogeeweb, 2018). In addition, copper wires function as the pathway for the electric signals and thus connecting the components. Its principal function is to facilitate electric connections and be mechanical support for the components. Therefore, the circuit boards are crucial for interconnecting an electrical product between its components (Bhunia & Tehranipoor, 2019). As can be seen in figure 1, which is a typical circuit board, the flat surface is characterised by a green colour.

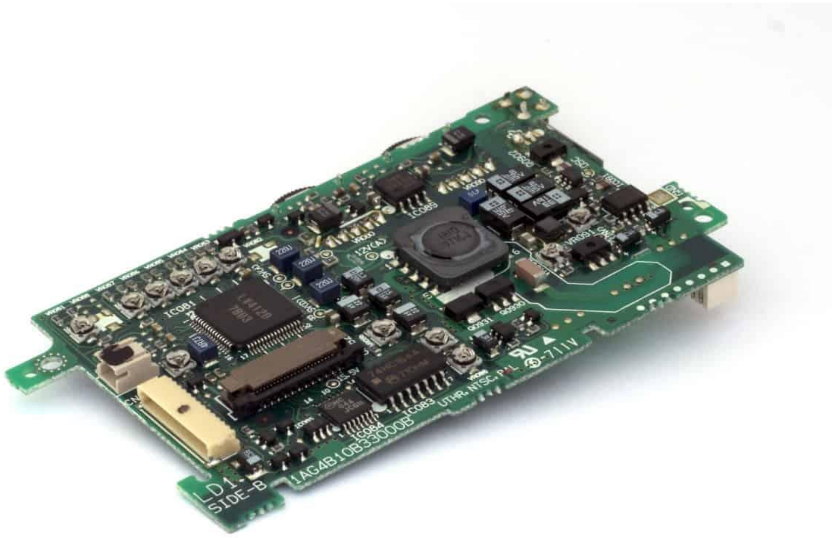

Figure 1. *Circuit Board*

Even though some versions of circuit boards have been around since the early 20th century, it was not until after world war two that the modern circuit boards were commercially used (Harper, 2003). In time more and more products have been electrified and connected. According to Yilmas (2008), the automobile industry has grown to be one of the most significant users of these types of components. During the last 30 years, many classic mechanical components have been replaced with electronic devices to reach the goals of stricter fuel economy and new emission standards (Yilmas, 2008). Additionally, safety, entertainment and information systems require a lot more electronic devices too, which also leads to higher demands for circuit boards.

One of the electronic components added to the circuit boards are semiconductors, the brain of every electronic device (Singal, 2022). According to Burkacky & Dragon (2022), no single market has all capabilities needed from design to manufacturing. However, some single markets have dominant positions for some of the needed phases. For example, Taiwan has a 52% share of all manufacturing while the US has 63% of chip design. Additionally, 66% of the wafer material that is a crucial material for the semiconductors comes from what Burkacky and Dragon (2022) refer to as "the rest of the world". The rest of the world are markets that are not the US, Europe, China, or Taiwan. During the 2020s, there has been a supply issue where the lead times have increased to at least six months longer (Burkacky & Dragon, 2022). According to Dobler & Heiss (2022), the automotive industry has taken a toll over a long period due to the shortages.

3.1 Circuit boards - Assembly

According to Yilmaz (2008), there are a few typical main steps in a surface-mount device (SMT) assembly process. The steps are screen printing, component placement, soldering, cleaning, inspection, and rework. Whether the circuit boards are single-sided or double-sided, the steps will have to be done one or two times. Screen printing is the addition of soldering paste needed for electrical connections on the circuit board. The currently most common method for screen printing is stencil printing which is performed by applying paste to the circuit boards by using a stencil designed to fill specific areas of the board with paste. Stencil printing is most suited for high volume production. The next step is the component placements, where components, also known as surface-mount devices (SMD), are placed directly onto the previously added soldering paste on the circuit boards. Component placement is generally the most demanding step in the assembly process, and this station is usually the bottleneck of the entire operation. Further, this station is most often the most expensive on the entire production line, where the placement machines can be up to 50% of the total capital investment for an SMT line (Yilmaz, 2008).

The circuit boards then go through a soldering station to secure the interconnections of the components added to the circuit boards. Popular techniques used in the soldering state are using infrared, hot vapour or laser. The circuit boards go through preheating, soldering and cooling in the furnace (Yilmaz, 2008). After soldering, the circuit boards must be cleaned from contaminants. When the circuit boards are cleaned, they need to be inspected and tested. As one of the quality controls, the circuit board is generally controlled through visual inspections, where optical cameras are the most common. However, lasers and x-rays are also common approaches for visual inspections. Additional electricity testing is often performed to ensure that the circuit board can lead electricity and function as intended.

4. Methodology

This section will present a thorough explanation of how every part of the project was conducted. It is divided into a general description of the methodology, how the data was collected, modelling of the simulation, experimenting done in the simulation, and lastly, a methodology reflection.

4.1 Research process

The project started with a planning period where everything supposed to be done was mapped out. Further, an estimation was made on how much time each phase would take. Once the planning was done, the project moved on to one of its main phases, data collection. For a simulation, it is, according to Skoogh, Perera and Johansson (2012), vital for the entire project to have good quality data. Since the project investigated only one product, the data gathering could only occur during the days when that particular product was manufactured. Theory gathering and the creation of the simulation, called modelling, happened parallel with the data collection to maintain productivity.

Once the modelling was done and all the data was collected, the next phase was initiated. It was experimenting with the model to test different ideas based on the theory of constraints about what could improve the actual production line. The simulations were extensive, so a lot of data were collected that needed to be summarised and analysed. With the results from the simulations, the last part of the project initiated with finalising the report and presenting the data to the concerned parties.

4.2 Research design

One company was examined due to the in-depth knowledge and data gathering required for a case study. When designing a case study experiment, the most important question is how its results can be representative and applicable to other cases (Bryman, Bell & Harley, 2019). The study's replicability was important to allow Veoneer to further investigate the ability to use DES to further improve their production, such as similar projects for the rest of the production lines. The overall design could be characterised as a representative or typical case as similar research has been completed before and is investigating an everyday type of situation (Bryman, Bell & Harley, 2019).

The project was mainly based on existing literature, which led to a deductive strategy. Further, the project had a quantitative approach since it mainly handled data consisting of numbers.

4.3 Literature review

According to Bryman, Bell and Harley (2019), The literature review is a foundation for any research project. Having a good overview of the subject makes it easier to determine what kind of research question needs answers, what concepts and theories have been applied to previous projects, and what research methods have been used.

During the literature review, information was gathered from databases such as google scholar and Chalmers library. Keywords used in these databases were, for example, Discrete event simulation, process theory, bottlenecks, simulations in manufacturing settings, circuit boards, and many more. The main point of these searches was to see what previous projects had done to avoid common pitfalls, see other benefits that had not been thought of, and find support and tips for securing the validation and reliability of the research.

Another point of finding good literature is to have solid theories to compare to the results and perform an accurate analysis. Even though a few of that type of theory was found in the previously named databases, most of this type of information came from physical books. These books were either already in our possession or borrowed from Chalmers Library.

4.4 Data collection

The data is of utmost importance in creating a discrete event simulation. Without key metrics, it will be impossible to get an accurate simulation of the actual production line and evaluate the simulation variables. Skoogh, Perera and Johansson (2012) identified four areas to collect data and visualise them in a figure that can be seen in figure 2.

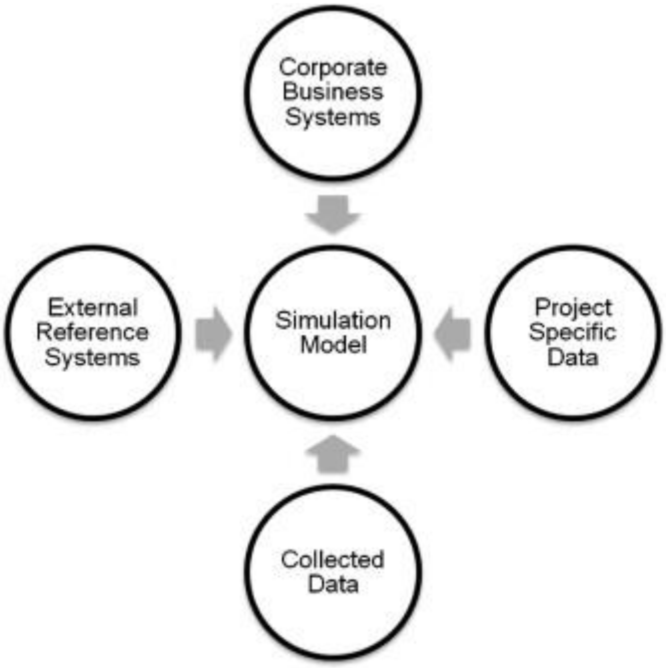

Figure 2. *Input data sources from Skoogh et al. (2012)*

Corporate business systems can involve a wide range of data, but operational data about the production line and its stations will be key for this particular project. For example, it can be data about the production cycle times, set up times, or frequency of breakdowns of machines (Skoogh et al., 2012). This type of data is usually secondary data that have been collected from others than the project team or automatically through the machines themselves (Skoogh et al., 2012).

Project-specific data for the project was information regarding typical order sizes needed to match the customer's orders. In comparison to corporate business systems, collected data is usually more primary data (Skoogh et al., 2012). For this project, observation of the production line and taking time on operations were done to complete the overall collected information. The collected data of the cycle times were manually clocked. The time was started when a circuit board entered the machine or conveyor and was stopped when the circuit board exited. This was to fit the simulation better but also due to difficulties of seeing the actual process on some machines. All times were measured at least ten times to remove disturbances and get an accurate average time that reflected the actual cycle time. Not only will the own collected data function as a complement to the secondary data but also as validation. The validation will be further discussed later in this chapter. External reference systems can include information for new machines to buy as a test to see what it will do to the overall production. For this project, none of these data types has been gathered.

To get access to the data and information, it has been required to talk to the key persons within the company. These people have primarily been working as process engineers for the production line. That includes the contact person at the company that has delivered information and data that we have asked for, contact information to people that could provide additional information, and provided access to software and databases needed to complete the project. Other people who have been influential in the sense of information and data providing are process owners who had more profound knowledge about the machines in the process line. They have, in most cases, provided reports with already processed data or files with raw data that we could work with.

The processed data has mainly been from Microsoft Excel, Leading2Lean, or software connected to the machines provided by the manufacturer. Data collected from databases at Veoneer or by observations are displayed following in table 1.

Data from Veoneer	Own observed data
Downtime minutes	Cycle times for machines and conveyors
Soldering paste usage	Frequency of micro stops
Yield from inspection machines	Time to complete the operator’s tasks
Usage of components from the placement machines	
MTTR on the placement machines	
Number of produced circuit boards during different intervals of time	
Reported micro stops	

Table 1. *Collected data*

All of the data and information were stored on Veoneer's cloud system. It was then accessible for both the Veoneer and us employees and done for two reasons. The first was that the employees of Veoneer should have access to the data we had gathered and use it for themselves and also to verify the correctness of the data we had collected. The second was to have the data secured safely without leaving the data to a third party and risk it leaking to a competitor.

A thorough analysis needs to be done to know how the data can improve the project. In most cases, the data was clear and could be used instantly with little analysis. One type of data that needed extended analysis was some reports taken from the previously named databases. In a few cases, the data did not say anything unless compared to other data types. It could be things such as data regarding the consumption of components and comparing it to data describing the number of circuit boards being produced at that particular time. These comparisons were mostly made in excel, where the data from the reports were imported and then merged, structured, and finally analysed.

In order to visualise the data excel and Microsoft Power BI was used. Additionally, some information was already well visualised in reports taken from Veoneer's databases. Some data could be visualised directly in tables and charts by the simulation software, where metrics such as utilisation, blockage and starvation could be displayed. The software also contributes to visual guidance, as recognising where and when a stop occurs in the production and what effects this has on the rest of the flow is clearer for the simulators.

4.5 Modelling and experiments

An essential part of modelling the process in a virtual environment is to make sure that it reflects reality. To avoid discrepancies between the simulation and the actual process, we made sure to validate the model by the process engineers at Veoneer before proceeding further. An error in this step would affect the whole project and generate a false outcome.

The model simulated how different production variables, such as MTTD, number of work-in-progress, and the frequency of micro stops, affect the flow and overall production time. When proceeding forward with the experiments, a trial and error approach was a suitable way to move on where established methods and theories were used to calculate estimates about areas of improvement. For example, since the X-ray machine was identified as the overall bottleneck due to it having the highest cycle time, one improvement included an extra x-ray machine to increase capacity. Another improvement tried to exploit the bottleneck as much as possible using buffers before and after.

Modelling the production started with a visit to the plant, where the focus was on sketching an initial layout on paper. This sketch was continuously updated as our understanding of the production grew from each visit to the factory. Several iterations of the layout were created before the final version was established and later verified by the contact person at Veoneer. Building the simulation in visual components started with a complete sketch of the layout.

In parallel to building the layout, we started investigating the programming logic for how each machine operated. This part required a significant amount of time and preparation by establishing the logic of each machine and the flow of the circuit boards themselves. The process for the programming logic took many iterations to get accurate as the machines perform advanced tasks, thus making the conditions challenging to program. This was done by continuous communication with the process owners of each machine and operators with experience working daily on the production line. Furthermore, through observations of the production, to make sure every conditional was accurate. Each programming function was first written on paper, followed by reviews of the solution. After that, the programming logic was programmed into the software to check if the solution was functional. This iteration was repeated until all conditions were behaving as expected, which verified the model.

During the investigation of the programming logic, we noticed that the production had irregular stops, which affected the production flow. Most of the time, these stops of conveyors, shuttles and machines were hard to notice when they occurred. This data will be referred to as observed micro stops. These micro stops had to manually be gathered from observations in the production. These observed micro stops can be contrasted to the reported micro stops that Veoneer already had some data on. We expand further on this under the Current state chapter.

Each machine's cycle time was added with a normal distribution time with a mean and standard deviation based on the collected data. Since some of the data fluctuated, the standard deviation was a tool to capture the variety in, for example, the frequency of micro stops, cycle times, and operator's work tasks. The aspect of randomisation provides a more fair representation of reality.

Every gathered production time, both for the original scenario and the improvements, was a calculated mean time of minimum five simulated runs. This was to mitigate the problem Pegden et al. (1995) identified to make sure no individual variable had a negative and significant effect on the resulting outcome. Data on MTBF were gathered on all machines but were decided not to be used. The reported numbers of MTBF were so large that they would not have impacted the simulations, as the times themselves were so much larger than the actual simulation time. For example, the machine with the lowest MTBF would require a simulation time 25 times longer than the original simulation time. Adding these numbers to the simulation would not make any difference to the simulation results since the machines would not have broken down during the simulated time. The placement machines were an exception, as the meantime between assists (MTBA) and MTTR metrics existed. The MTBA contributed with accurate data in both frequency and length. The data on MTBA covers the MTTD, MTTR and MTBF for all types of stops. With a fixed MTTR value, the MTTD will not change on the placement machines for the different simulated MTTD values.

4.6 Analysis

The analysis will be based on the experiments performed from the virtual model. The goal of the analysis was to draw conclusions about which simulation variables have the highest impact on the process's overall output performance. With all of the different MTTD, improvement suggestions, and number of simulations per scenario for statistical significance, the total number of simulations was 220 times. In other words, 220 different times and correlations to keep track of. To see what difference aspects, such as an improvement or a variation in MTTD made, an excel file was created to keep track of all this data. Having a good structure of the data both in terms of helping to visualise it, as well as to interpret the visualisation and draw conclusions.

4.7 Methodology reflection

Discrete event simulation was chosen as it was the objective from Veoneer to evaluate the method for testing improvements of the production. Alternatively, one could perform a manual mapping of the process and do all calculations by hand. However, this had already been tried by one of Veoneer's engineers without success. The process is far too complex to consider all of the moving variables in the production line.

There are also alternatives to the simulation software that could perform equally well for the project. However, we chose this software due to previous experience with it, thus leading to reduced time in the learning stages of the program.

A key improvement factor for further studies or work regarding data collection could be to gather information over the available data set as early as possible. Much time went towards figuring out what data existed, making it hard to predict what data needed to be manually gathered and which data gathering needed the highest priority. The data were also scattered among several key persons, making the gathering process slow and inefficient. Another factor contributing to a suboptimal data gathering was that some data was hard to interpret, most because each machine or process had structured the data in different ways and could be interpreted in multiple different ways. Having a more thorough breakdown session of how to navigate between all of the folders could have saved some time. Additionally, some time for all of Veoneer's employees can be saved by improving the folders' structures and cleaning up unnecessary things such as empty folders.

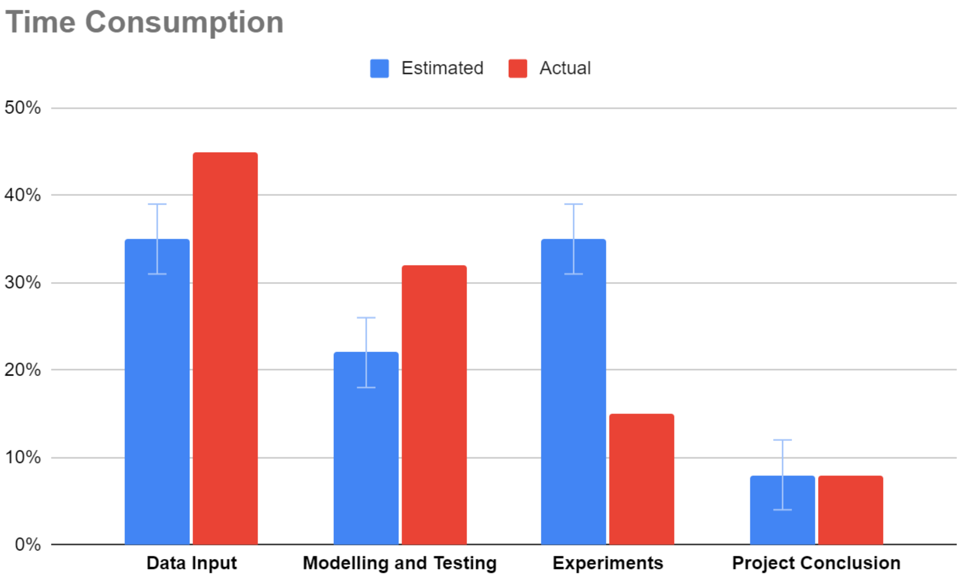

Figure 3. *Estimated vs Actual time consumption of the project*

Had the data been in place earlier and during the expected time schedule, more conclusive experiments regarding the improvements could have been performed, as can be seen in figure 3. This could also have made it possible to simulate more products, enabling a comparison of the improvements between different articles making the results more trustworthy. Simulating only one type of product gives useful improvement suggestions, but it does not give an understanding of how these improvements affect different products.

We were not allowed to gather data on the MTTD metric from the operators, which increased the number of simulations that needed to be performed. The effect of this was that we needed to simulate six different scenarios having MTTD varying from 0 minutes to 5 minutes on each tested improvement. This time could have instead been used to evaluate more improvements.

The observation of the micro stops themselves could be inaccurate due to randomised outcomes of the occurrences, as well as that they are difficult to notice. Furthermore, they affect the production time to a high degree and, therefore, would need more validation to increase the reliability of the results in an optimal case.

4.8 Reliability and validation

Reliability is the matter of consistency of measures and is divided into different parts. The first is the matter of stability, which concerns whether the data is stable over time (Bryman, Bell & Harley, 2019). It can be tested by doing multiple tests and getting the same results. For example, the clocking of cycle times for the project has been at least done ten times per machine to get a stable and accurate meantime. The stability has also been tested in the simulations, where each scenario has been simulated at least five times.

Internal reliability is about whether a data point differs depending on changes in other factors or if it remains consistent. For example, when examining some work steps performed by the operators, the data gathering was spread across multiple days to make sure the set of operators would not give different results.

Validity is the aspect of whether the collected data actually measures the intended object (Bryman, Bell & Harley, 2019). Face validity has been common during the project, which means making sure the collected data actually represents the subject requested by asking people with expertise on the subject.

To really understand what the data meant, communication was key. By having dialogues with the contact person and other process owners that were experts on some types of data, it was possible to understand and interpret the data in-depth. Further, it was a chance to see if the conclusion from the analysis had accurate information or if the analysis lacked anything.

5. Results

This chapter will account for the results found during the project. The result is divided into two sections, Current state and Simulations. The current state will give a description about how the production line is today and provide detailed information about for example machines or work tasks for the operators. The Simulations will provide a thorough explanation about the results from the simulation in form of bar charts, describing text, and comparisons between the different improvements.

5.1 Current state

One of the main issues is to find enough data to come as close to reality as possible to answer the research questions. By doing a current state analysis of the production line, many data points, such as cycle times, breakdown frequencies, etc., were collected for the simulation model.

The layout of the SMT-006 is roughly designed like figure 5. Conveyors are connected between each station to transport the circuit boards. At point A in figure 5, the production line starts with the top side of the circuit boards. The first station is a marking machine that uses a laser to mark every circuit board with a code. Every machine on the production line can read the code to identify the circuit board and its needs. The laser is followed by a soldering paste application station, called DEK, where a paste is applied to the circuit boards. Right after the DEK, a counter keeps track of the number of circuit boards in the loop, set to a maximum of 65. This counter is visualised as an upward-facing triangle in figure 5 called Counter In. Next, the circuit boards go through an inspection machine called SPI to see if the applied paste from DEK is good enough in terms of quantity and quality. The circuit boards then continue to the placement machines, adding components to the circuit boards.

There are three placement machines, and each of them has two lanes, one for the top side circuit boards and one for the bottom side. A single placement machine has four placement heads that can work simultaneously and manage four circuit boards in total. They are often divided to only work on the top sides or the bottom sides, but the machines can also operate asynchronously, which means that a placement head can work on both lanes simultaneously.

As shown in figure 4, the bottom side is being managed by placement head 1 and 2, while the top side is being managed by placement head 3 and 4.

When the placement machines are done, the circuit boards go through a soldering station, a tunnel where heat is applied to re-melt the paste. After soldering, a buffer is needed to cool down the circuit boards. The last step of the process for the top side of the circuit boards is the AOI, where the circuit boards are being examined to see if the components have been rightly placed on the circuit boards, and the x-ray station, where the soldering process is being audited. If an error is found, the circuit boards are being reviewed by an operator at an inspection station, where they either get rejected or allowed to continue.

At point B in figure 5, the circuit boards go right and are flipped to the bottom side, then proceed for a second lap in the loop. The bottom side's processing starts with the second soldering paste application station, called DEK 2. After the second lap, the circuit boards exit the production line at point C and are checked by the ICT, ensuring that all electrical signals work as intended. After the ICT, another counter is placed to count down, allowing Counter In to enable new circuit boards to enter the loop. A downward-facing triangle visualises this counter in figure 5 called Counter out.

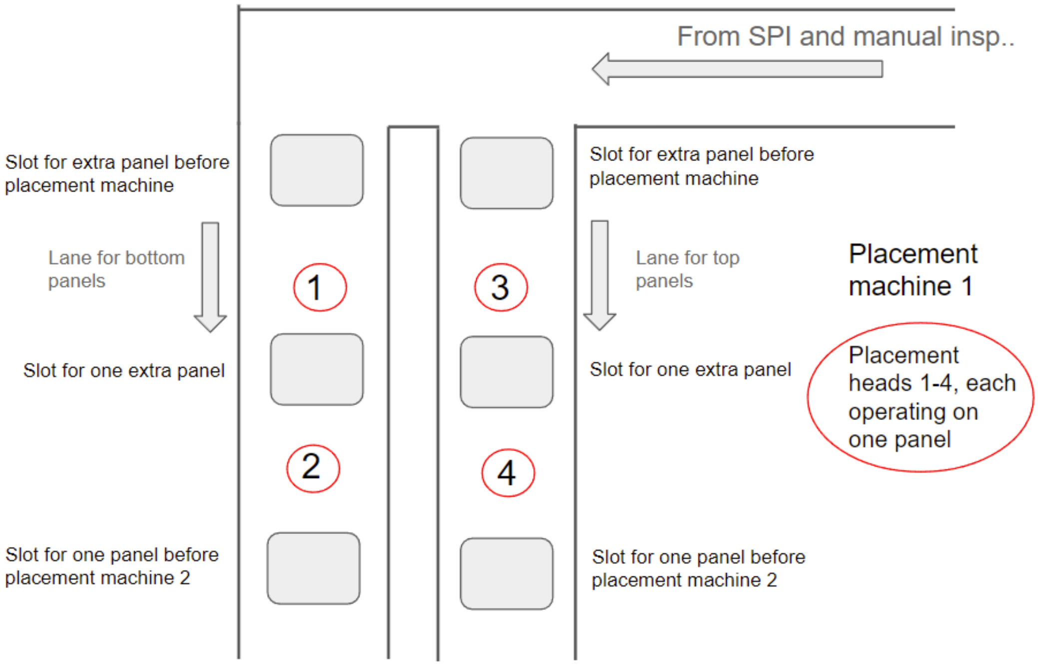

Figure 4. *Display of placement machine 1 with 2 lanes & 4 placement heads*

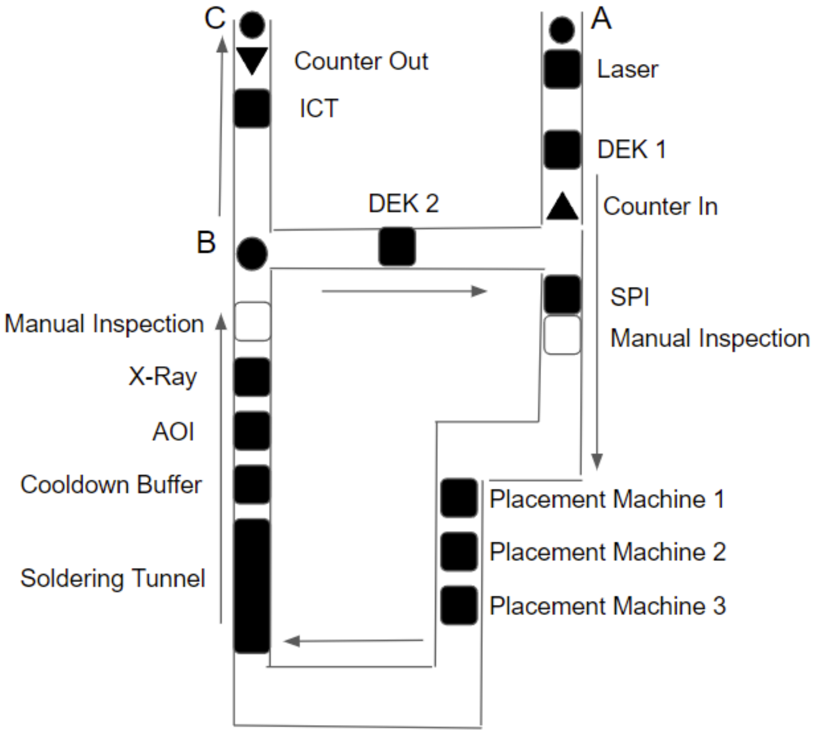

Figure 5. *Simplified Current Layout*

There are two, sometimes three, operators available to assist the production line. Their tasks include setups when changing the produced articles, some tasks handed out by operators such as changing or cleaning instruments in the machines, inspection of possible faulty products, and handling breakdown of machines. When a machine requires assistance, a visual system alerts the operators. The visual system can either be green, orange or red. In addition, there is an additional auditory system for some stations to alert the operators.

The bar chart of figure 6 showcases a visualisation of the ideal cycle times per process for the top side of the circuit boards. The blue bars are cycle times, and the red bars are the difference in cycle times compared to the bottleneck. In this case, it is one of the placement machines. When doing the top side of the circuit boards, the sum of the blue bars is 69.5 per cent of the total theoretical time for the production line. The sum of the red charts is then 30.5 per cent which is the amount of balancing losses for the top side.

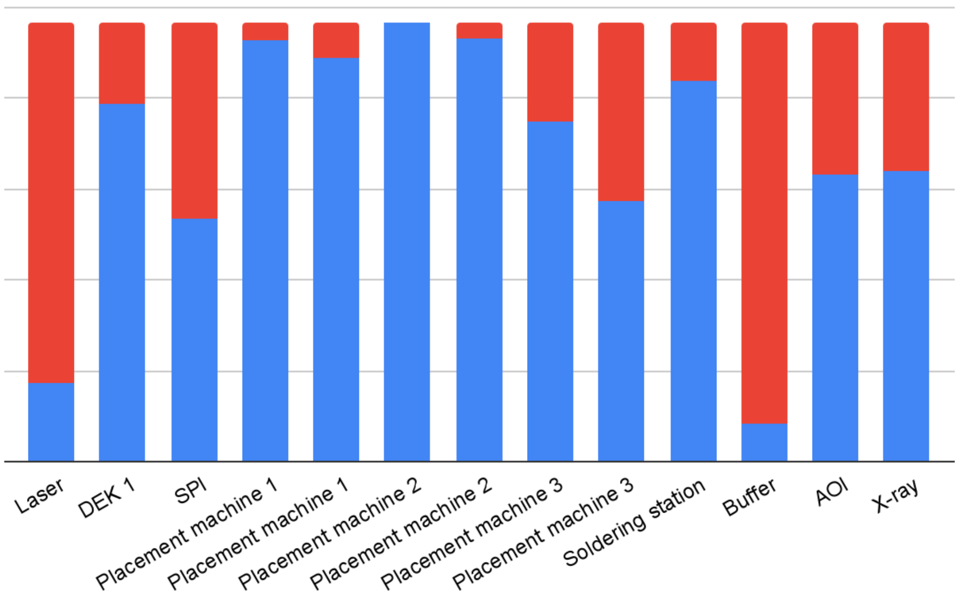

Figure 6. *Bar chart on the balancing losses for top side circuit boards*

For the bottom side, the visualisation is done in figure 7, where it is possible to see that the bottleneck is the x-ray. This process takes the longest overall time when comparing all cycle times for both sides, making this process the production line's overall bottleneck. For the bottom side, the sum of the blue bars is 57 per cent, and the sum of the red charts is 43 per cent. It is worth mentioning that these cycle times are only for a specific product and the cycle times change depending on the products. So the bottleneck for other products might be somewhere else than the x-ray.

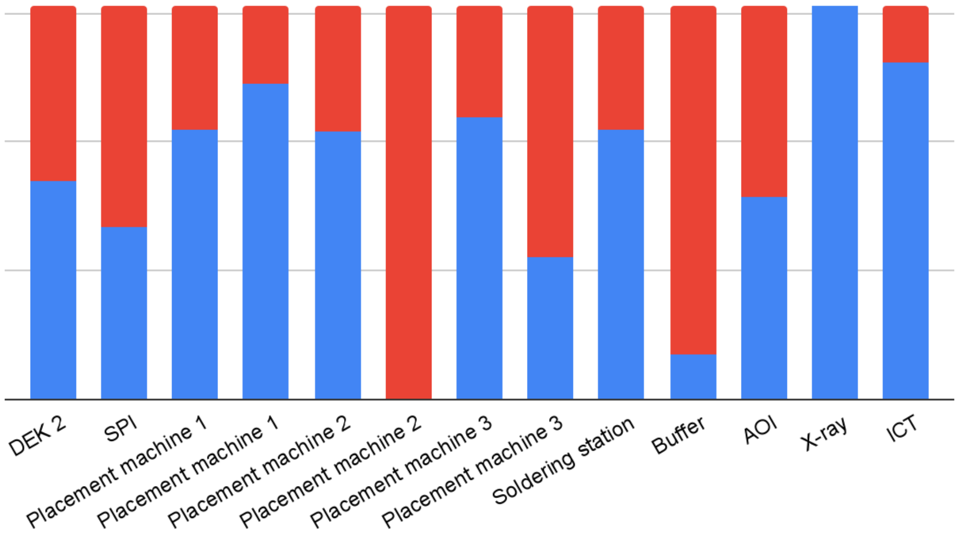

Figure 7. *Bar chart on the balancing losses for bottom side circuit boards*

As can be seen later in this section, the operators' part and involvement in the production are a vital part of the productivity. Their tasks are to manually check suspected errors on the circuit boards when the inspection machines alert them and maintain the processes within the production line in a matter of replenishing paste for the solder machine and changing various instruments. Additionally, they should fix minor errors or stoppages at the machines and conveyors and alert the process owners of the machines when major breakdowns occur. Visual aids in the form of lights beaming in different colours are placed on top of most of the machines to help the operators know when their assistance is needed. Some of the machines also have alarms.

Even though Veoneer tracks micro stops, they only had data on stops that, on average, were more than 5 minutes long, and an absolute majority of the stops were 10 minutes or more. This data was summarised and sorted to find the most common places for the longer micro stops. The most common micro stops happened right before the soldering station, and the accumulated frequency of these was once every 194 circuit boards. Because of the low frequency, the micro stop will practically only occur one time in the simulation. If the reported micro stops had been placed separately, they would never occur during the simulated time due to a significant discrepancy between each reported micro stop's simulated time and frequency. The frequency was calculated using the following equation:

$$\frac{total\ manufactured\ units}{number\ of\ reported\ micro\ stops} = reported\ micro\ stop\ frequency$$

The placing of the stop in the simulation model is visible in figure 8 as a reported micro stop. Worth mentioning is that the other stops happened at multiple other stations in the production line. Since this point was the most common, it was selected as a base point for all other stops. This stop was calculated to be 17 minutes long and added to the simulation with a 0-minute MTTD since the metric already was included in the stoppage time.

During the collection of cycle times, there were some signs indicating a few micro stops in the production line that were not accounted for in Veoneer's databases. By doing three different observations for 1-3 hours with a total time of 6 hours, a frequency of the observed micro stops could be established. In conclusion, there were an average of 14 stops per hour that lasted less than 5 minutes each. In figure 8, the distribution of these stops is mapped out, where the numbers showcase the frequency of stops per hour. The work time required to correct the observed micro stops was relatively low. However, the layout of the production line makes it difficult for the operators to notice when the stoppages occur. During the data collection and small talks with the operators, a few requests for additional visual aids were conveyed. The time to notice when the operator is needed for an event is referred to as the MTTD metric. Unfortunately, no data existed on the MTTD metric, and it was not possible to collect it due to requests from the union. MTBA, the mean time between assists, and MTTR were available from a different data set for the placement machines. Therefore, the stops for the placement machines were simulated with a fixed MTTR and MTTD metric. These metrics correlated with the observed micro stops visualised in figure 8, indicating that the collected data is reasonably accurate. A few different scenarios regarding the MTTD metric have been tested where the metric was altered from 0 up to 5 minutes. We estimate that the mean detection time should be around 0-1 minute with an improved alerting system.

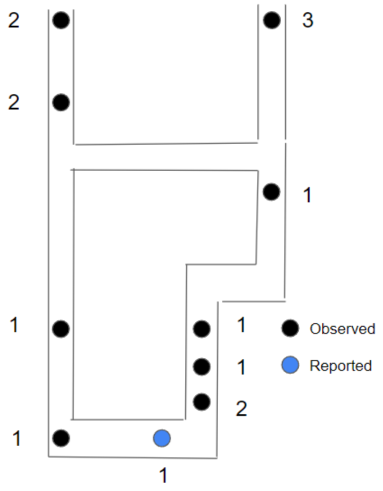

Figure 8. *Frequency of micro stops per hour - both observed and reported*

Another thing affected by the MTTD metric is the inspection of suspected defect circuit boards. The inspection yield is classified information according to Veoneer but was used in the model as a simulation variable. A manual inspection handles yields from the SPI right after the station. Furthermore, another manual inspection station is located after the x-ray station, auditing the yield from both the AOI and x-ray.

Since the operator's tasks affect the production line, adding all of their tasks to the simulation was necessary even if it did not stop the production. It was to consider their available time and how it could affect other areas of their work described above. It was things such as how much time the operators spent on a method called splicing. Splicing is when the operators add new components to the placement machines when the machines' current components are about to run out. By looking at the number of splices and the number of produced products, the following equation could be derived:

$$\frac{quantity\ of\ produced\ units}{quantity\ of\ splicing\ activities} = number\ of\ produced\ units\ per\ splicing$$

It was possible to see a need for splicing for an average of every 64 products from the equation. Additionally, the operator's tasks included maintaining the machine's material consumption by changing stencils, cleaning the soldering stations, and changing cleaning rolls. Cleaning the soldering stations was done with such a low frequency that it was neglectable, and changing the cleaning rolls after the laser was done every 100 circuit boards. Finally, soldering paste usage for both DEK 1 and 2 was calculated by the amount of paste each circuit board uses compared with the amount of paste in the tube. The results from calculating the solder paste usage showed that a change of tubes was needed for every 1356 top side at DEK 1 and 1205 bottom side at DEK 2.

5.2 Simulations

All experiments were tested based on the most common order size determined by Veoneer. In this case, it was 10 batches containing 25 circuit boards each, for a total of 250 circuit boards. In total, 220 simulations were carried out, each recording the total production time.

A baseline for the production time of producing the 250 circuit boards was established by simulating the original layout both with and without the reported and observed micro stops. After that, each improvement was compared to the baseline time to understand its significance to the overall production time. Finally, the baseline production and each improvement were simulated with an MTTD of 0, 1, 2, 3, 4, and 5 minutes to understand how much each simulation variable affects the production time. Veoneer had two improvement suggestions that they wanted to test with the motivation to increase the utilisation of the placement machines and to get an even balance between top-and bottom-side circuit boards. These are improvements 1 and 2 that will be accounted for later in this chapter.

5.2.1 Production results without any improvements

Figure 9 compares the overall production time of the original production to the production time of adding the reported micro stops, the observed micro stops, and an MTTD of 0 to 5 minutes. The variation of each scenario with the fastest and slowest production time is visualised in figure 10. Figure 11 shows the same results based on a percentage comparison. The percentage shows how much slower the production gets for each scenario than the ideal production without micro stops.

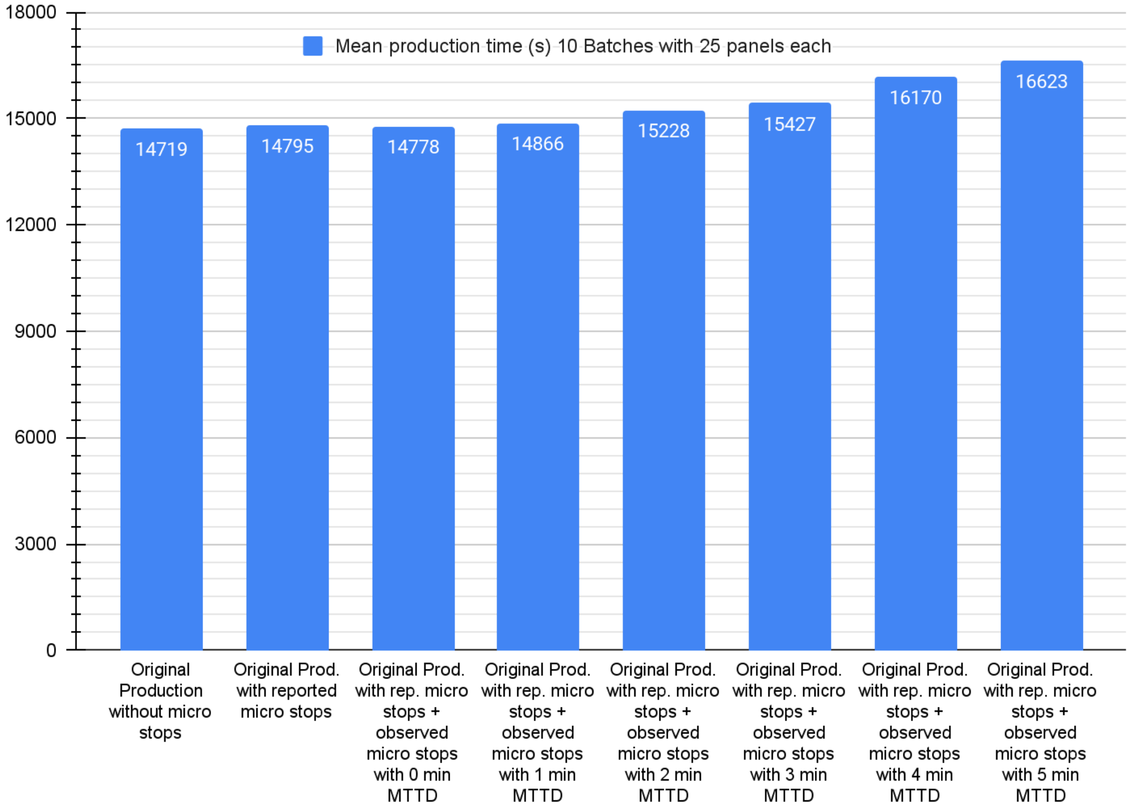

Figure 9. *Total production time in seconds from different scenarios*

The results show that the production time increases with added micro stops, both the company's reported micro stops (+0.5% production time) and the observed ones (+0.4% production time). The production time also increases based on the MTTD. A 1-minute MTTD to each micro stop accounts for a 1% slower production, whereas the MTTD metric over 1 minute has a higher contributing effect to the overall production time. A 2-minute

MTTD results in a 3.5% slower production time, and a 3-minute MTTD leads to a 4.8% slower production. The highest percentage point gain to the production time comes when the MTTD increases from 3 to 4 minutes; here, the production time is 9.9% slower than without any micro stops and 9.4 percentage points slower than with reported micro stops. The highest contributing factor to a slow production is when the mean time to detect is 5 minutes, contributing to a 12.9% slower production time.

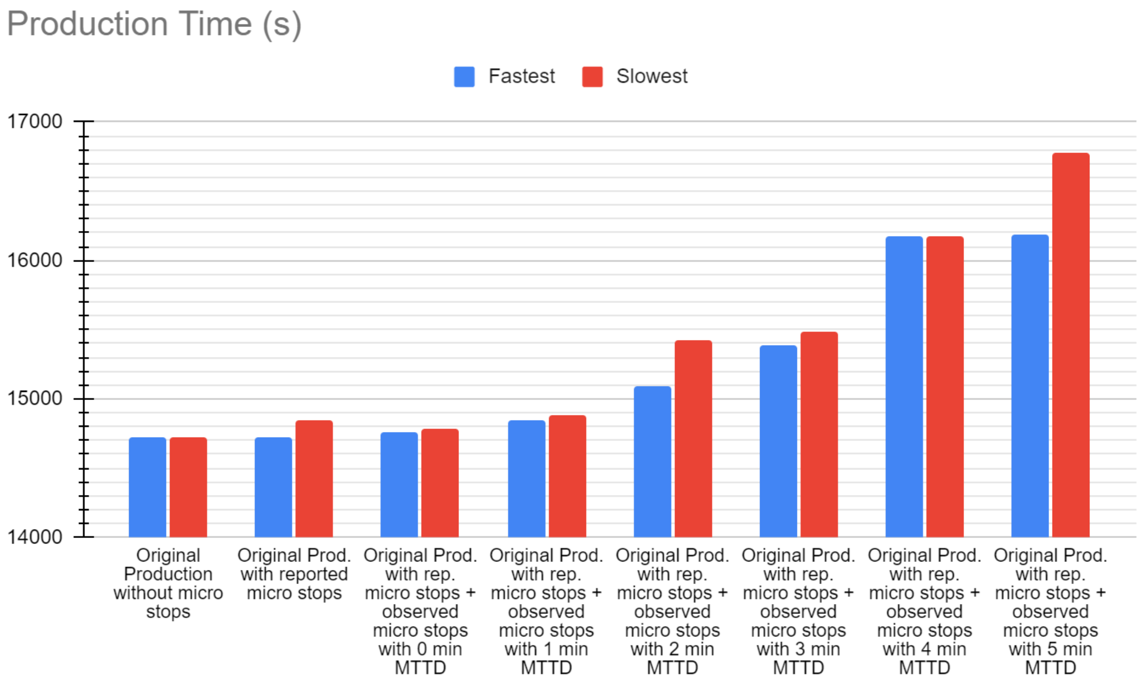

Figure 10. *Fastest & Slowest simulated time for each scenario*

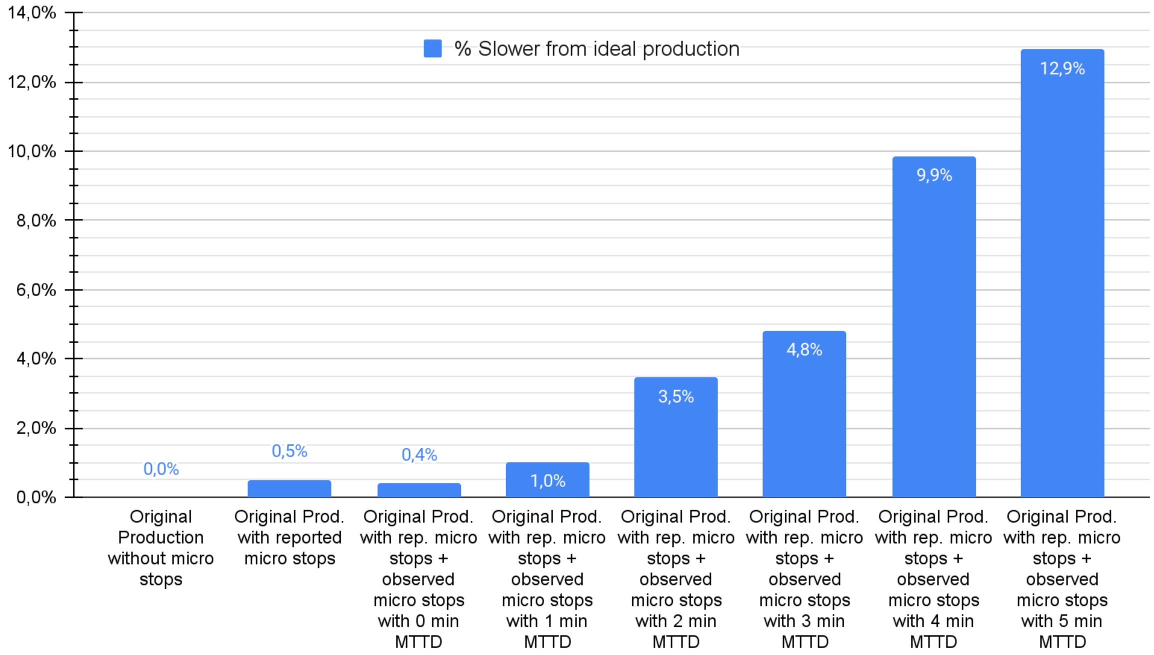

Figure 11. *Percentage slower of different scenarios compared to ideal production*

The baseline production time is compared to the original production, including the reported micro stops and the observed ones; this is depicted in Figure 14 in grey colour. The reason is to get a more representational view of how the improvements affect the actual production. The other alternative would have been to compare the improvements to the ideal production without micro stops. However, this is deemed unrealistic as there will always be some form of micro stops that needs to be managed by the operators. The difference overall between ideal production and observed micro stops is 0.4%.

5.2.2 Tested Improvements

Improvement 1 added an additional counter that will keep track of the number of circuit boards in the loop that is faced upwards. This improvement was one of two suggestions Veoneer wanted to test. The underlying motivation behind this improvement is to get a better balance between upward-facing circuit boards with downward-facing circuit boards in the loop. The improved balance may lead to a better flow as the placement machines get utilised more. The simulations were performed, with the counter keeping track of the total number of circuit boards, with 60, 65 and 70 total circuit boards in the loop and with 35 upwards facing. No significant difference in the production time was recorded when changing the total amount of circuit boards in the loop. The optimal amount of total circuit boards was dependent on the MTTD. However, 65 circuit boards were the original amount and were deemed the most optimal. The simulations were also performed with 30, 32 and 40 upward facing circuit boards without any improvements in the production time compared to 35 upward facing circuit boards.

Improvement 2 was to add a buffer before the placement machines, which sorts the circuit boards to send out every other upward-facing with every other downward-facing. This improvement was the second suggestion that Veoneer wanted to test. The motivation behind this improvement is similar to the first improvement. It intends to increase the utility of the placement machines by making sure both lanes in the machine have circuit boards to operate on and that the machine itself is not starving. This improvement also ensures that the SPI never gets blocked when the placement machines break down, enabling fewer circuit boards to be stuck. The simulations were performed with the buffer's capacity of 10 to 16 circuit boards, taking the same amount of upward- and downward-facing circuit boards. For example, if the total capacity is 10, the buffer takes 5 upward- and 5 downward facing circuit boards.

Improvement 3 was to add two buffers, one buffer placed before the x-ray, which is the identified bottleneck for the downward-facing side of the circuit board, to minimise the time that the x-ray is starved. The other buffer is placed right after point B in figure 6 when the circuit boards are headed toward point C. This buffer intends to alleviate the time the x-ray is being blocked due to a high frequency of micro stops near the last machine and enable the x-ray to operate for a maximum amount of time. The simulations were run with a capacity of the buffers between 2 to 7 circuit boards each.

Improvement 4 was to add an additional x-ray machine. Its motivation was to break the bottleneck and increase its production rate, which resulted in a faster throughput time. Figures 12 and 13 illustrate the new cycle times after increasing the capacity of the x-ray. The new balancing losses for the circuit boards processing the upside are 33% (figure 12) and 37,9% (figure 13) for the downside, compared to the original losses of 30,5% and 43,1%.

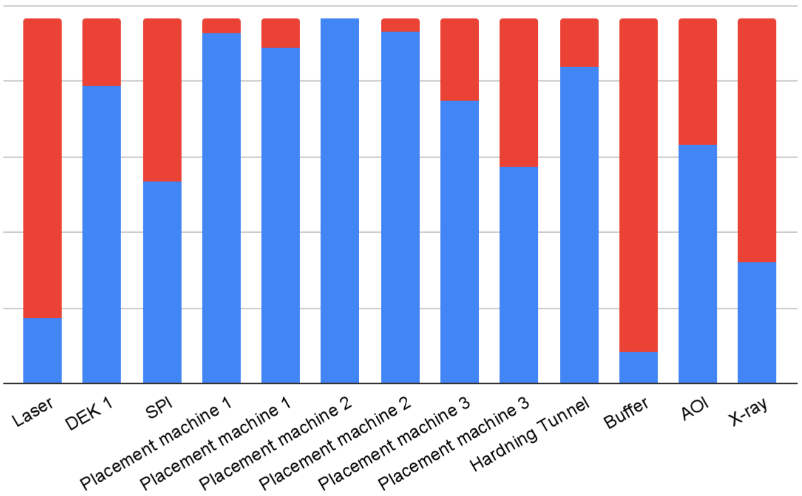

Figure 12. *Balancing losses of Top side with improvement 4.*

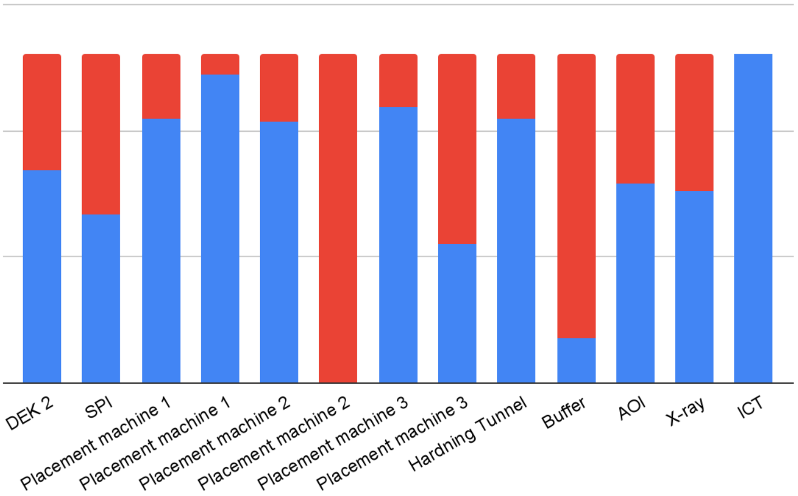

Figure 13. *Balancing losses of Bottom side with improvement 4.*

Improvement 5 was to reduce the frequency of the observed micro stops to half. The reduction was to understand how much the frequency contributes to the production output versus the mean time to detect metrics.

5.2.3 Results from tested improvements

Figure 14-17 represents how each improvement affects the overall production time. Figure 14 compares the different production times (in seconds) to each improvement and the MTTD metric. As the column diagram shows, each improvement's production time increases with the MTTD. The effect of increasing MTTD from 0 to 1 minute is close to neglectable but starts to increase in significance after 2 minutes and upwards.

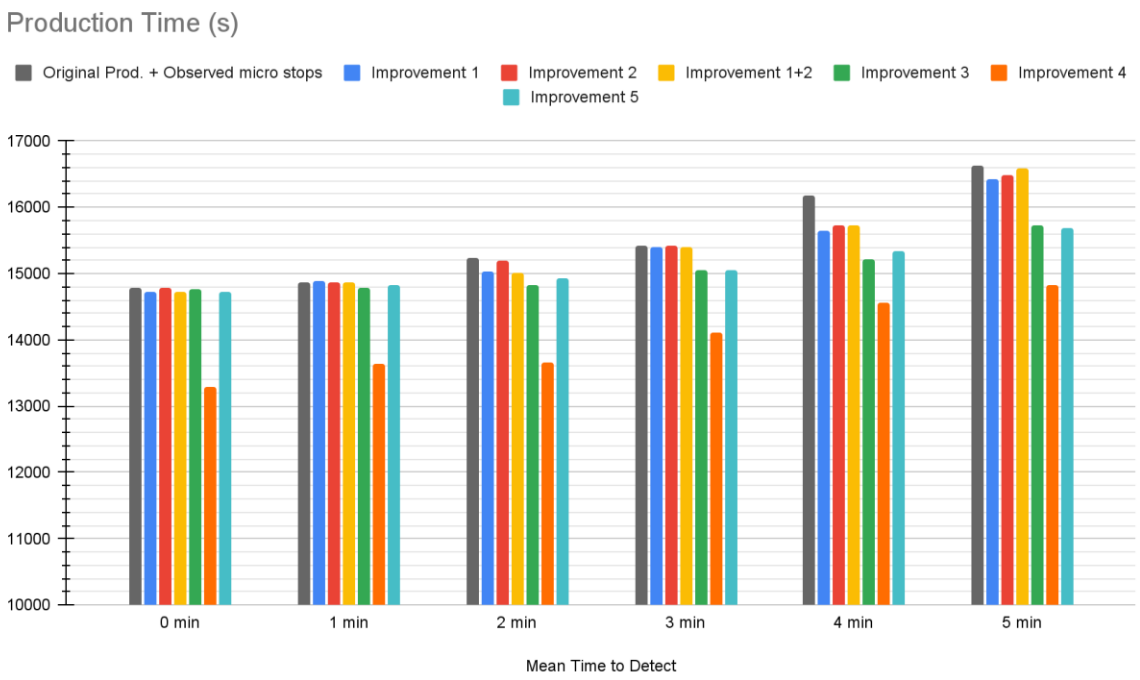

Figure 14. *Production time of different improvements based on MTTD*

Figure 15 shows the percentage difference of the improvements with the corresponding MTTD value to understand better the impact each improvement has on the production time. A positive percentage value indicates a faster production time than the original production with the corresponding MTTD, while a negative percentage difference indicates a slower production.

Improvement 5's first significant impact on the overall production time was with an MTTD of 2 minutes and above. With a 2-minute MTTD, the production time improved by 1.9% and 2.5% with a 3-minute MTTD. The highest impact on the production time was with a 4 and 5-minute MTTD, where the improvements were 5.2 and 5.6%.

Improvement 4 was the only improvement that significantly reduced production time on all simulated MTTD metrics, with the lowest impact of 8.3% (1 minute) and the highest of 10.8% (5 minutes).

Improvement 3 had no impact with a 0 minute MTTD and a low 0.5% decrease on a 1 minute, but its significance increased thereafter. On an MTTD of 2 minutes and upwards, its lowest percentage decrease to the production time was 2.4% (3 minutes), and its highest was 5.9% (4 minutes), better than the original production.

Improvement 1+2 only had two significant impacts on the production time, with a 2-minute MTTD, 1.4% faster, and a 4-minute MTTD, 2.8% faster.

Improvement 2 had little to no impact on the total production time with an MTTD of 0 to 3 minutes. However, with a 4-minute MTTD, improvement 2 had a 2.7% faster production time than the original layout. Lastly, with a 5-minute MTTD, the overall improvement was 0.8% faster.

Improvement 1 had a negative impact on the production time on a 1-minute MTTD and little to no effect on a 0 minute and a 3-minute MTTD. However, with a 2 and 5-minute MTTD, the improvement resulted in a 1.3% respective 1.2% faster production time. Finally, the improvement had its most significant impact on a 4-minute MTTD, where the improvement led to a 3.2% decrease in the production time.

Figure 15. *Percentage increase or decrease of production time with corresponding MTTD*

Figure 16 and 17 give a representation of how much the MTTD metric itself contributes to the production time when applying the different improvements. Figure 16 compares each improvement to the original layout with a 0 min detection time to the observed micro stops, and Figure 17 does the same but with a 1 min detection time. A positive percentage difference indicates that the improvement is faster, whereas a negative percentage difference indicates that the improvement is slower.

Figure 16 shows that only improvement 4 contributes to a decrease in the production time compared to the original layout with a 0 min MTTD if the improvements themself have an MTTD of 1 minute and over. Improvement 1 and improvement 1+2 contribute to a 0.4% and 0.3% faster production time on a 0 minute MTTD as shown in figure 16. No other improvement than improvement 4 contributes to decreased production time compared to the original production with an MTTD of 0 minutes.

Figure 16. *Percentage increase or decrease of production time compared to 0 min MTTD*

Figure 17 compares each improvement to the original production with a 1-minute MTTD. All improvements are faster when having a 0-minute MTTD. On a 1 minute MTTD, the results are the same as in figure 15. When simulating with a 2-minute MTTD, only improvement 3, 0.3% faster, and improvement 4, 8.1% faster, has a faster production time than the original layout. On an MTTD of 3 minutes and above, only improvement 4 positively impacts the production time. On a 5 minute MTTD, improvement 4 still has a slight improvement of 0.2%.

Figure 17. *Percentage increase or decrease of production time compared to 1 min MTTD*

Figure 18 showcases the percentage of the overall bottleneck, the x-ray station, being busy operating on a circuit board. Otherwise referred to as utilisation. Only improvements 3 and 5 were compared to the original production in this case as these were the only improvements with a motivation to elevate the bottleneck. Improvement 4 decreases the throughput time of the x-ray, which shifts the bottleneck and is therefore not represented in this comparison. Improvements 3 and 5 have a higher utilisation on all simulated MTTD times than the original layout. The difference is negligible up to 1 minute but starts to increase thereafter. On a 4 and 5 minute MTTD, the difference between the original production and the improvement is 5 to 6 percentage points.

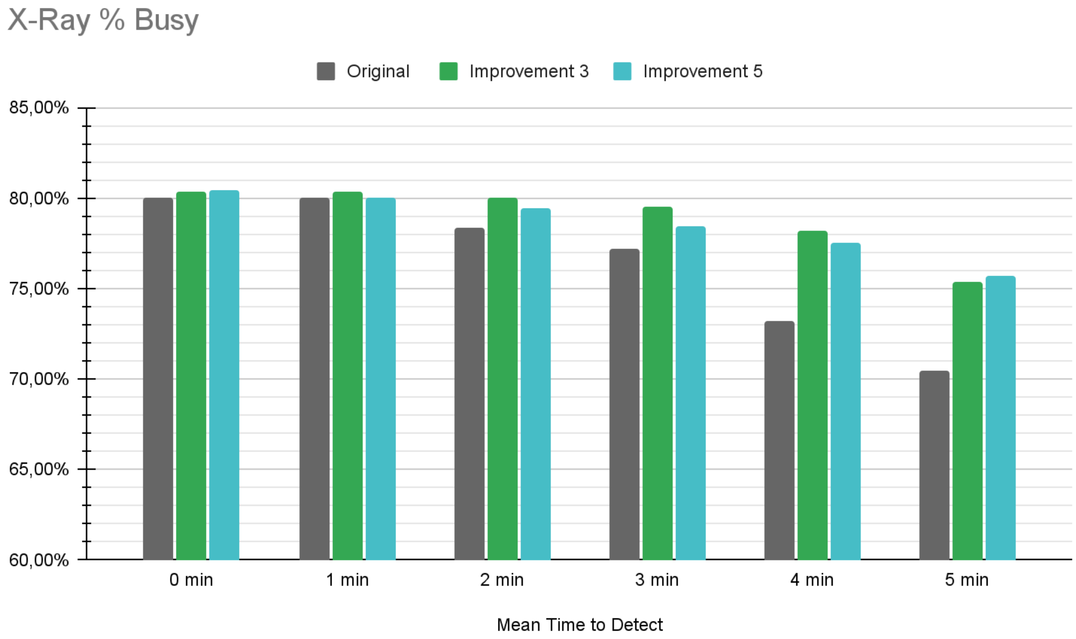

Figure 18. *X-Ray percentage busy*

Figure 19 compares the percentage rate the x-ray is being blocked. Only improvements 3 and 5 are compared with the same motivation as in figure 18. The same result was concluded from simulating with an MTTD of 0 to 3 minutes. On a 4 minute MTTD, the x-ray is blocked 1.5% of the time with the original layout, 0.8% with improvement 5 and 0.4% with improvement 3. Improvement 3 had the best result with the highest percentage blocked of 0.5% on a 5-minute MTTD. On the same MTTD, the original was blocked 4%, while improvement 5 was blocked 1.25% of the time.

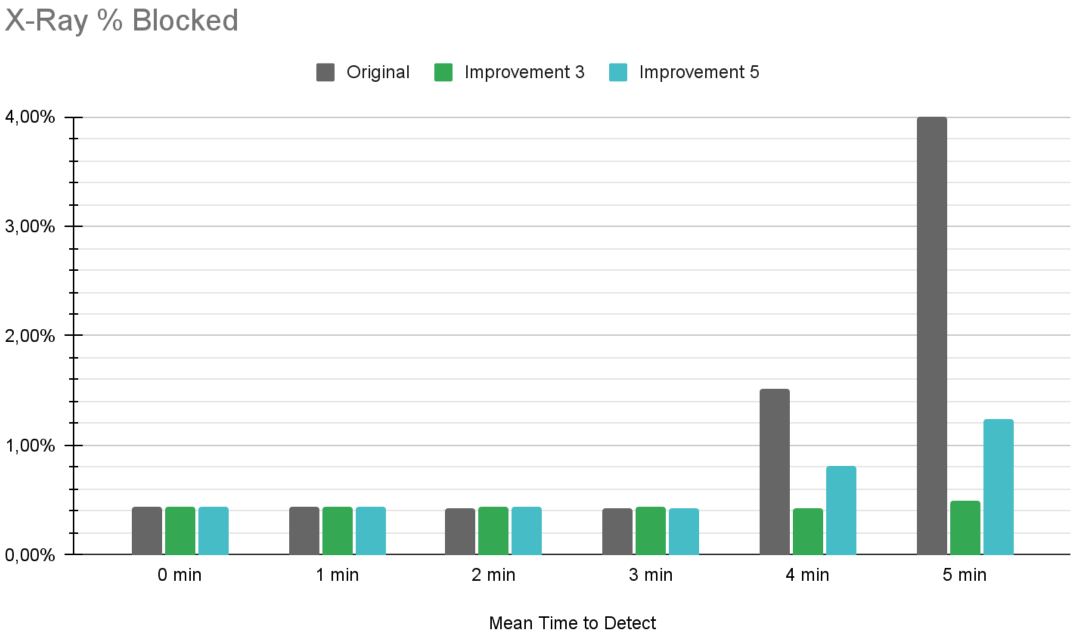

Figure 19. *X-Ray percentage blocked*

6. Analysis & Discussion

This chapter will talk about tested- and potential improvements. First, on tested improvements, analysis and discussion are made regarding each tested improvement's effects. Then, in the subheading, Potential improvements, analysis and discussion are made regarding other findings suitable for the company.

6.1 Tested improvements

As the results showed, the production time increases with the MTTD metric. The increase is because when a micro stop occurs, the products in the following stations have to wait for the operator to fix the fault. The wait time leads to a stoppage with earlier machines in the layout getting blocked directly and machines after getting starved, resulting in lower utilisation of these machines. In some cases, there is a buffer between the machine and the fault, which enables some machines to keep working even though there is a stop ahead. However, when the MTTD is longer, the buffer's capacity is not enough to cover the entire stoppage time, thus creating a blockage for the previous stations. As shown in figure 8, four stops occurred per hour in the last part of the production layout, reaching from point B to point C in figure 5. When having a higher MTTD, these stops lead to the x-ray getting more blocked, as showcased by figure 19. When the x-ray gets blocked, the overall throughput time increases because it is the overall bottleneck of the production. Blocking the x-ray is the opposite of what is advocated in the theory of constraints, where it is emphasised to exploit the bottleneck to a maximum. It also has a negative impact on the performance objective of speed and cost as the total production time increases, which leads to fewer products being produced than with an optimal production flow. The more the x-ray is blocked, the more it impacts the production time, as can be seen by comparing figure 19 and figure 11.

The highest increase of a loss in production time occurs when the MTTD increases from 3 to 4 minutes. Figure 18 showcases that the utilisation of the x-ray decreases with an increase in the MTTD due to an increase in blockage and starvation. The starvation can be calculated by looking at the utilisation (figure 18), which drops more than the increase in blockage (figure 19). The starvation contributes to an increase in waste and reduces the capacity due to additional waiting time. The starvation occurs due to both the observed micro stop from figure 8 right before the AOI and the reported micro stop from Veoneer. Another thing to note about the MTTD is that the production time is not linear to the increase to the metric as the production time increases exponentially with an increase to the MTTD value. The increase to the production time might also be an effect of the blockage and starvation that occurs to the x-ray after a 4-5 minute MTTD.

Improvement 3 tried to alleviate the blockage and starvation problem by adding one buffer right after point B (figure 5) towards the exit to exploit the x-ray to a maximum. The improvement enables the downward-facing circuit boards to stack up while the other can continue on its second loop instead of getting stuck before point B (figure 5). The other buffer was placed right after the AOI, which enabled some products to stack up, as the X-ray's throughput time of the x-ray is slower than the AOI, which allowed the x-ray to keep on processing circuit boards when the micro stops occurred. Figure 15 showcases that improvement 3 had a positive effect on the production time when simulating an MTTD of 2 and 3 minutes with a ~2.5% decrease in overall time and an even higher effect on a 4 and 5-minute MTTD of ~5.5-6% faster production. The improved output is due to the increased utilisation, which can be seen in figure 18 and from a decrease in percentage time being blocked (figure 19). The improvement increases the performance objective of speed. It also affects the performance objective of dependability as the added buffers lead to a more stable production time indifferent to the MTTD values by neutralising the effects caused by the micro stops. The increase in performance leads to waste reduction in the form of waiting time for the most important station. Additionally, the cost objective may get more reliable as the production time is more stable during an MTTD of 0-4 minutes.

Improvements 1 and 2, both separately and combined, did not contribute in a significant way to improving the production time. This may be because the motivation behind both improvements was to optimise the utilisation of the placement machines, which in turn showed that it did not have the effect on the production time as had been estimated from Veoneer. One of the placement machines is the bottleneck for the upward-facing circuit boards, but not overall, and the effect seems to be lowered when the production line itself has the number of micro stops that it does. The improvements were insignificant on the lower simulated MTTD values, except for a 1% faster production with a 2-minute MTTD. However, they did affect the time on a 4-minute MTTD with about ~3% but declined again at a 5-minute MTTD. The insignificance of these improvements might be because of the blocked x-ray, which seems to have a higher-order effect than the placement machines on the overall production time.

Only one product was simulated, and even though other products might be similar, the results are not enough to draw conclusions about those products. However, longer MTTD values and micro stops that are not accounted for in the data will affect the production regardless of the variant of the product being produced. Since the other products have different cycle times for each station, improvements 1, 2, or both combined could have a more significant effect on products which have the placement machines as their overall bottleneck. The purpose behind improvements 1 and 2 was to increase utilisation of the placement machines, which would make them interesting to test on a different product with the placement machines as the bottleneck. This is in line with the theory of constraints, which emphasises maximising bottleneck usage.

Improvement 4 was based on point 4 in the theory of constraints to elevate the bottleneck by increasing its capacity. The increase in capacity was done by adding another x-ray to the production, which worked parallel to the first one. As can be seen from the results, this improvement had the most significant effect of all, as it allowed for the throughput time of the x-ray to decrease significantly. The lowered throughput time strengthens the performance objectives for both speed and cost, as the overall production time can be lowered considerably. Since the throughput time gets reduced, speed is improved. Cost is affected by increased speed since a lower throughput time reduces the tied-up capital on work-in-progress. Furthermore, it should result in higher output in terms of revenue. The fixed costs can be divided by a larger quantity of units and thus reduce the unit cost. The added x-ray contributes to a more even symmetry of the balancing losses between the machines, which increases the overall utilisation of the production line and decreases the balancing losses. The balancing losses were around 2,5 percentage units worse for the top side and 5,2 percentage units better for the bottom side. It also moves the theoretical stationary bottleneck, which should be the ICT, placement machine 1 or placement machine 2, according to the bar charts in Figures 12 and 13. The bottleneck may be floating between these machines depending on the production flow and the micro stops, both reported and observed.

All improvements led to a faster production time when compared to the original production with the corresponding MTTD, except improvement 1 and improvement 1+2 on 1 min

MTTD. When comparing the original production and a 0-1 minute MTTD, only improvement 4 positively affects the production time. This suggests that the MTTD value itself has a higher significance than any improvement suggestions, except for improvement 4, which overall improved all MTTD. However, we were not allowed to gather the actual value of MTTD, and each observed micro stop was simulated with the same detection time for every improvement. Due to the layout of the production line, some stops may be challenging to detect, and thus the same detection time might not reflect the actual production exactly.

Nonetheless, the results show a significant impact on the MTTD metric and should be considered the highest contributing simulation variable to the production time. We think that an optimal MTTD should be somewhere between 0 and 1 minute. This optimal MTTD value could be achieved by adding more visual aids to notify and help the operators during their work.

The micro stops add additional throughput time where the stoppages occur, increasing the overall production time more than the improvements decrease it. This leads to waste as it increases the waiting time for some machines. Halving the frequency of the micro stops does not have a significant impact when comparing improvement 5 to the original production with a 1-minute MTTD in figure 17. This further strengthens the hypothesis that the MTTD is the highest contributing simulation variable to an overall increase in the production time. The lowered output leads to a significant drop in the performance objective of speed and increases the cost as overall efficiency drops with an increase to the MTTD metric.

6.2 Potential Improvements

As mentioned in the theory chapter about Lean Management and, more specifically, about signals, it is found to be more efficient with two sets of signals. However, it could also make operators subject to habituation due to constant exposure, where they will not notice the signals as much as wanted. A solution could be other signals such as hearing and visual signals where the operators could have armbands or similar connected to the production line, and when a machine is alarming, the armband gives off vibrations. It would reduce the redundancy of auditory signals on the factory floor. It could also be beneficial to collect all data on a single screen to give the operators a better view of the entire production area. During Genchi Genbutsu, small talks were held with the operators, and a few of them expressed a desire to have the alarms gathered in one place to see better where there is a stoppage. With the argument of not wanting to waste the employees' unused creativity while also possibly improving the waiting time, the improvement is worth investigating. A third possible improvement could be to have a change in the work routines for the operators where they could walk around more in the production line to see if there are stoppages they have not noticed. We think this is a good idea due to the high frequency of machines and conveyors breaking down without alerting the operators via a noise signal.

Even though many product variations are created on all SMT-lines, one potential improvement could be to have individual production lines specially adjusted to some of the products. For example, SMT-006 could be specially adjusted for the focused product and others, which also has the x-ray as an overall bottleneck, and target the production of the mentioned products to that particular line. Furthermore, it is important to have the capacity to manufacture other products and remain flexible for the demand. This could be further investigated by simulating with data from other products.

As was eminent during the project, some data were either hard to find or did not exist. This is an area of improvement where we believe Veoneer can enhance their processes in developing their operations to make their analysis and estimates more reliable. More data regarding the frequency and time of the observed micro stops that were not accounted for in Veoneer's data is required and could add additional insight by helping them understand the effect on potential improvements such as better visual aids. This could also help them improve on the frequent stops and understand why they occur. However, investigating why the stops occur was outside the project's scope but should be the primary focus before implementing potential improvements on capacity. Further, more data would enhance the work with simulations for their other SMT lines and other manufacturing operations. For this project, with already gathered cycle times, it would have been possible to simulate more products and thus have more empirical results to compare. Simulating several products would also entail the inclusion of all downtime metrics for the machines, contributing to a more accurate result from the simulation.

A significant improvement could be to add another x-ray to the production. According to the simulations, an added x-ray could benefit Veoneer as the production time can be reduced and capacity increased by 8-10%. Unfortunately, no data on the financial cost of an additional x-ray was gathered, so no recommendation on this can be made. However, if the cost of another x-ray is less than the cost saved on a shorter production time, it could be justified to acquire one.

Another aspect of investing in additional x-rays could be to analyse the long term aspect of capacity. For example, there is a question regarding the expansion of Veoneers SMT production lines to meet long term demand growth. However, with 9 current production lines, it would be beneficial to investigate the solution to investing in additional equipment for existing production lines. It would save space but could save the company much money. As stated in the section about circuit boards, placing machines could be up to 50 per cent of the overall capital investments. By investing in other machines for the current production lines, there is no need for investments in additional production lines and thus additional placement machines.

6.3 Ethics and sustainability

During this project, some social and economic sustainability encounters have been made. By lifting the subject of the alarming systems, a potential improvement in the operators' working conditions may have been found. When having the right tools to alert the operators, stress from worrying about potential stoppages might be reduced. By improving the alerting systems, aspects such as improving key figures might lift the staff's morale.

When talking about sustainability, it is essential to lift the economical aspects. By having an efficient production line, the company can improve their financial position. With a strong financial position, the company manages to live on and continue to manufacture products that help people and potentially can save lives every day in the form of safety equipment.

7. Conclusion

7.1 What simulation variables have the greatest effect on the overall production output?

Based on the results from the simulations, the simulation variable with the greatest contributing effect to the overall production was the MTTD metric. The overall production time increases with an increase to the MTTD. MTTD values of 5 minutes contribute to a 12.9% total loss from ideal production due to a slower production time.

Another simulation variable with a significant effect on the output was the number of micro stops that occurred during production that was not accounted for in the data. These stops affect the overall production output as it lowers the utilisation of key machines. However, the frequency of these stops does not contribute to the overall production time as much as the MTTD value does. Some micro stops occur in places without a signalling moment, which increases the MTTD value. These stops need more evaluation to understand why they occur and how to lower their frequency. In addition, additional investigation is necessary to help alert the operators when stops occur.

The total amount of circuit boards in the loop had a little contributing effect depending on the MTTD value but was deemed most optimal at the original amount of 65 circuit boards.

7.2 What improvements have the greatest effect on the overall production output?

The improvement with the highest contributing effect to the production time was improvement 4, adding an additional x-ray. The added x-ray had an 8-10.5% decrease in the total production time, indifferent to the MTTD metric.

Improvement 3, which were two added buffers, supports the productivity of the production by alleviating some disturbances that occur to the bottleneck on higher MTTD values.

Overall, our recommendation to Veoneer is to further improve their understanding of the frequency of the micro stops and examine the MTTD metric. Investigating why these stops occur should also be the priority before implementing improvements to capacity, as these stops decrease the amount of value-added time to the production. The MTTD values could vary in time depending on where they occur, further improving the simulation model. The simulation itself can act as a base for further expansion to investigate other products, more simulation variables, and how the suggested improvements would affect those products. With more simulated products and a longer simulated time, the model could include the MTBF values not accounted for in this study. This would further strengthen the understanding of how the more prolonged stoppages affect the production line.

References

Alexander, A. (2021, March 09). How the West Abandoned Manufacturing in Favour of a Service Economy, Causing a Decline in our Standard of Living. Retrieved from https://www.oxford-royale.com/articles/west-economy-misbalanced-services-manufacturing/

Anjoran, R. (2021, September 21). How to Avoid Production Bottlenecks with Lean Methods and Tools. Retrieved from: https://www.cmc-consultants.com/blog/how-to-avoid-bottlenecks-in-production-with-lean-methods-and-tools

Apogeeweb. (2018, October 12). Differences between IC and PCB: Composition,Characteristics and application examples. *Apogeeweb Electronics*. https://www.apogeeweb.net/article/130.html

Aspentech. (2022). *What is the main cause of downtime in manufacturing?* AspenTech. https://www.aspentech.com/en/apm-resources/manufacturing-downtime

Asprova. (n.d.). *Yield - Material planning*. MRP Glossary of Production Scheduler Asprova. Retrieved May 18, 2022, from https://www.asprova.jp/mrp/glossary/en/cat248/post-729.html

Barone, A. (2022, February 08). Understanding Bottlenecks. Retrieved from https://www.investopedia.com/terms/b/bottleneck.asp

Bellgran, M., & Säfsten, K. (2010). *Production Development: Design and Operation of Production Systems.*

Bergman, B., & Klefsjö, B. (2012). *Quality from customer needs to customer satisfaction*. Studentlitteratur.

Burkacky, O., de Jong, M., & Dragon, J. (2022, April 15). Strategies to lead in the semiconductor world. McKinsey & Company. https://www.mckinsey.com/industries/semiconductors/our-insights/strategies-to-lead-in-the-semiconductor-world

Harper, C. A. *Electronic materials and processes handbook*, McGraw-Hill,2003 ISBN 0-07-140214-4, pages 7.3 and 7.4

Chung, C. (2004). Simulation modeling handbook: A practical approach. Boca Raton: CRC Press.

Cox, J. F., & Schleier, J. (2010). *Theory of constraints handbook*. McGraw-Hill.

Dobler, S., Heiss, C. (2022). *Semiconductor shortage*. Oliver Wyman. Retrieved May 18, 2022, from https://www.oliverwyman.com/our-expertise/insights/2022/feb/semiconductor-shortage-in-the-auto-industy.html

Haraszkó, Csaba & Nemeth, Istvan. (2015). DES Configurators for Rapid Virtual Prototyping and Optimisation of Manufacturing Systems. Periodica Polytechnica, Mechanical Engineering. 59. 143-152. 10.3311/PPme.7888.

Jahangirian, M., Eldabi, T., Naseer, A., Stergioulas, L.K., Younga, T. Simulation in manufacturing and business: a review, European Journal of Operational Research 203 (2010) 1–13.

Johansson, B. (2006). On Virtual Development of Manufacturing System: Proposal for a Modular Discrete Event Simulation Methodology [Thesis for the degree of doctor of philosophy, Chalmers]. https://www.researchgate.net/profile/Bjoern-Johansson-9/publication/235719391_On_Virtual_Development_of_Manufacturing_Systems_-Proposal_for_a_Modular_Discrete_Event_Simulation_Methodology/links/5ec46351a6fdcc90d685d5ec/On-Virtual-Development-of-Manufacturing-Systems-Proposal-for-a-Modular-Discrete-Event-Simulation-Methodology.pdf

Jonsson, P., & Mattsson, S. (2016). Logistik: Läran om effektiva materialflöden. Studentlitteratur.

Keim, R. (2020). What Is a Printed Circuit Board (PCB)? - Technical Articles Retrieved from https://www.allaboutcircuits.com/technical-articles/what-is-a-printed-circuit-board-pcb/

Klaver, E. (n.d.). *Production line dynamics: What counts is what actually comes out of your line* (p. 1). Assembleon. Retrieved May 18, 2022, from https://smtnet.com/library/files/upload/production-line-dynamics.pdf

Lee, F., Chan A., Attending Visual and Auditory signals: Ergonomic Recommendations with Consideration of Signal Modality and Spatial Stimulus-response (S-R) Compatibility, International Journal of Industrial Ergonomics, 2007, 37, 197-206

Li, L., Chang, Q., & Ni, J. (2009). Data driven bottleneck detection of manufacturing systems. *International Journal of Production Research, 47*(18), 5019-5036. doi:10.1080/00207540701881860

Holweg, M., Davies, J., De Meyer, A., Lawson, B., & Schmenner, R. (2018). Process Theory : The Principles of Operations Management: Vol. First edition. OUP Oxford.

Mourtzis, D., Doukas, M., & Bernidaki, D. (2014). Simulation in Manufacturing: Review and Challenges. *Procedia CIRP*, *25*, 213-229. doi:10.1016/j.procir.2014.10.032

Ocampo, L. A., Clark, E. E., & Liggayu, A. (2012). Effect of Noise and Redundant Auditory Alarm Signal on Semiconductor Production Operators' Response to Machine Downtime. *Noise & Vibration Worldwide*, *43*(11), 21–28. https://doi.org/10.1260/0957-4565.43.11.21

Pegden, C.D., Shannon, R.E., Sadowski, R.P., 1995. Introduction to simulation Using SIMAN, 2nd Ed., New York: McGraw-Hill.

Pehrsson, L., Ng, A. H., & Bernedixen, J. (2016). Automatic identification of constraints and improvement actions in production systems using multi-objective optimization and post-optimality analysis. *Journal of Manufacturing Systems*, *39*, 24-37. doi:10.1016/j.jmsy.2016.02.001

Roser, C., Nakano, M., & Tanaka, M. (2002). Shifting bottleneck detection. *Proceedings of the Winter Simulation Conference*. doi:10.1109/wsc.2002.1166360

Singal, N. (2022). How the semiconductor chip stopped the world. *Business Today*. Retrieved May 18, 2022, from https://www.businesstoday.in/magazine/industry/story/how-the-semiconductor-chip-stopped-the-world-316710-2021-12-27

Sisense. (2020). *Mean time to detect KPI*. Sisense. https://www.sisense.com/kpis/it-kpi/mean-time-to-detect/

Skoogh, A., Perera, T., & Johansson, B. (2012). Input data management in simulation – Industrial practices and future trends. Simulation Modelling Practice and Theory, 29, 181–192. https://doi.org/10.1016/j.simpat.2012.07.009

Slack, N., Chambers, S., Johnston, R., Hicks, C., Lewis, P., & Yang, Y. (2011). *Operations management*. Pearson Education.

Slack, N., & Lewis, M. (2020). *Operations strategy*. Pearson.

Statistis.com: The Institute For Statistics Education. (2022). *Continuous vs. Discrete Distributions.* https://www.statistics.com/glossary/continuous-vs-discrete-distributions/

Stamatis, D.H. (2010). The OEE Primer : Understanding Overall Equipment Effectiveness, Reliability, and Maintainability. Productivity Press.

Subramaniam, S. K., Husin, S. H., Singh, R. S. S., Hamidon, A. H. H., 2009, Production Monitoring System for Monitoring the Industrial Shop Floor Performance, International Journal of Systems Applications, Engineering and Development, 2009, 3(1)

Swarup Bhunia, Mark Tehranipoor, Chapter 4 - Printed Circuit Board (PCB): Design and Test, 2019, Pages 81-105, ISBN 9780128124772, https://doi.org/10.1016/B978-0-12-812477-2.00009-5.

Trubaciute, V. (2020, February 18). *The six big losses in manufacturing*. Evocon. https://evocon.com/articles/the-six-big-losses-in-manufacturing/

Visual Components. (2022). *A world leader in 3D simulation*. Visual Components. https://www.visualcomponents.com/about-us/

Westrom, D. (2022, February 18). The Growing Use of Automation in Manufacturing. Retrieved from https://www.machinemetrics.com/blog/automation-in-manufacturing

What is Lean?: Lean Thinking. (2021, December 03). Retrieved from https://www.lean.org/explore-lean/what-is-lean/

Wilcox, S., A Human Factors Perspective Auditory Alarm Signals, Biomedical Instrumentation & Technology, July/August 2011, 284-289

Yilmaz, I. O. (2008). *Development and Evaluation of Setup Strategies in Printed Circuit Board Assembly*. Gabler Verlag.

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