USING SIMULATION FOR A NEW PRODUCTION LINE AT PHILIPS DRACHTEN

Master Thesis by Vincent Strijker

UNIVERSITEIT TWENTE.

Preface

This thesis is the result of my internship at Philips Drachten and part of the final assignment of my Master Industrial Engineering & Management with a specialization in Production & Logistic Management. During my internship I have gotten a lot of support from great people and I would like to thank them.

Firstly, thanks to Jeroen Geidanus and Roel Hoekstra for guiding me on a daily basis during my research. Because of them I had everything I needed within Philips Drachten. From quick feedback to connecting me with the right people. It was a pleasure cooperating with them.

Secondly, I like to thank my supervisors at the University of Twente, Ahmad Al Hanbali and Leo van der Wegen. Their feedback was very valuable and much appreciated.

I would also like to thank all the employees at Philips Drachten who I came in contact with, my colleagues for half a year. They made the entire internship a great experience I will remember for a long time.

Lastly, I want to thank all my family and friends and especially Rianne van Asperen, who have all supported me during this time and during my entire studies. My studies are finally completed now, it was a good time.

Vincent Strijker
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Summary

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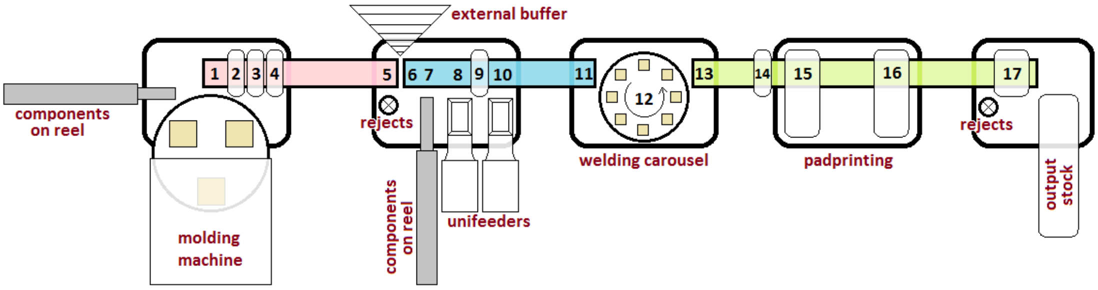
Philips Drachten has invented a brand new shaving product. In order to mass produce this product, a brand new production line will have to be engineered and set up. Philips Drachten needs to know how this production line can be set up in such a way that production targets are met and waste is minimized. The production line will look as follows:



The system consists of 17 machines divided over 5 production cells. The cells are connected by three carrier loops, which contain molding-carriers (red loop), assembling-carriers (blue loop) and printing-carriers (green loop). The first cell contains the overmolding machine which should be stopped as rarely as possible due to degradation of the plastic that it uses. Breakdowns are expected for each production cell, after a breakdown the cell will need to be repaired. There is limited space for buffering carriers and breakdowns can cause starvation and blockage at other machines. At machines 2,4 and 17 the products are tested; products that fail the test are taken out of production (this happens with a fall off rate). Products can temporarily be stored in an external buffer between the first and second cell. This external buffer exists to maintain a steady production at the overmolding machine in the first cell. This steady production is desired because the materials used in this process will degrade if they are not used in time.

The objective of this research is to provide Philips Drachten with recommendations on what size the external buffer should be, how many carriers to place in the assembly line and how to allocate the available buffer space among the machines. To reach this objective the following research question is used:

> *What is the effect of the number of carriers and the allocation of buffer places within the assembly line on the throughput of the assembly line and on the starvation/blockage of the overmolding machine?*

Method:

To answer the research question a simulation model is built and validated. The model is then used to find the effects of the following variables:

- Varying combinations of assembling-carriers and printing-carriers.
- Varying distributing of available in-line buffer space between the cells.
- Two combinations of molding cycle times with different fall off rates.
- Two sets of cycle times (all machines at 3 seconds and all machines at 2 seconds).
- Varying combinations of failure rates and repair rates of the production cells.
- Varying cycle time of the welding carousel, which turns out to be the bottleneck.

Cycle time here is defined as the time spend per product from the moment a carrier enters the machine up until the processing is finished, not including break downs.

The following performance measures are used:

- Production rate (amount of products produced per shift).
- Overall equipment efficiency (production compared to the theoretical maximum).
- Amount of products stored in the external buffer.

Main findings

The main findings after running the model are that the target production of 5.5 million products per year (i.e. 6111 products per shift) can be obtained by using 9 molding-carriers, 9 assembling-carriers and 8 printing-carriers.

The expected overall equipment efficiency of 77% cannot be reached, even when the most effective amount of carriers are used and the buffers are allocated in the most effective way. This most effective situation requires 9 molding-carriers, 16 assembling-carriers and 28 printing-carriers. The buffers should be allocated in such a way that between the Assembly Cell and the Welding Cell there are 7 places for buffering carriers, between the Welding Cell and the Printing Cell there are 9 places for buffering carriers and between the Printing Cell and the Packaging Cell there are 6 places for buffering carriers.

A molding cycle time of 2.5 seconds with 22% fall off rate results in about the same system performance as a molding cycle time of 3 seconds with 5% fall off rate.

By improving all machines such that they have a cycle time of 2 seconds, will not give the expected production of 10 million products per year.

By improving the failure rates and repair times very big improvements can be made. For instance if the mean time before a cell breaks down is improved by 33%, then the production rate increases by about 7.5%, which results in about half a million extra products produced per year. If the mean time before a cell is repaired is reduced by 20%, then the same improvement of about 7.5% is reached for the production rate.

By reducing the processing time of the welding carousel (which is the bottleneck of the assembly line) to 2.25 seconds, the production rate increases by about 1.3%.

By having an initial stock in the external buffer, the production line can cope with unexpected breakdowns of the overmolding machine. When an initial stock of 2000 products is used, then the external buffer rarely runs out of products.

The increase in products in the external buffer rarely exceeds 2000 products. This means that when the initial stock of 2000 products is used, the buffer never exceeds 4000 products.

Recommendations

The following recommendations are made towards Philips Drachten:

- Use 9 molding-carriers, 9 assembling carriers and 8 printing-carriers.
- Allocate buffer space such that between the Assembly Cell and the Welding Cell there are 7 places for buffering carriers, between the Welding Cell and the Printing Cell there are 9 places for buffering carriers and between the Printing Cell and the Packaging Cell there are 6 places for buffering carriers.
- The external buffer should be able to hold 4000 products. An initial stock of 2000 products should be tried to be maintained.
- If the external buffer is full, shut off the overmolding machine and restart this machine when the stock in the external buffer drops below 2300.
- Decrease the processing time of the welding carousel.

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List of Symbols

Constants and variables

c1	Number of molding-carriers
c2	Number of assembling-carriers
c3	Number of printing-carriers
FPY	First Pass Yield
loop	Set of all machines in a carrier loop
m	Machine number
OEE	Overall Equipment Efficiency
PA	Process Availability
PP	Process Performance
PT	Processing Time
TT	Transportation Time
rc	runcounter

Units

s	Seconds
hr	Hours
wk	Weeks
shift	Shifts
yr	Years
#	number (mostly refers to amount of products or carriers)

List of Abbreviations

BWM	Bremer Werk für Montagesysteme
FOR	Fall Off Rate
FPY	First Pass Yield
MTTF	Mean Time Till Failure
MTTR	Mean Time To Repair
NPI	New Product Introduction
OEE	Overall Equipment Efficiency
PA	Process Availability
PP	Process Performance
TTF	Time Till Failure
TTR	Time To Repair

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1 Introduction

This thesis is part of the final Master assignment for the study Industrial Engineering & Management at the University of Twente. It describes research conducted at Philips Drachten to help in the design and optimization of a new production line. This chapter starts with a description of the company and the department where the research is carried out in Section 1.1. This is followed by the problem description in Section 1.2 and the research scope in Section 1.3. After this, the research objective (Section 1.4) and the research questions (Section 1.5) are presented.

1.1 Company Description

Philips Drachten is part of Royal Philips N.V., which is a multinational technological company that aims to improve lives by offering meaningful innovations. Royal Philips was founded in 1891 as a company producing light bulbs and quickly grew to be one of the largest producers in Europe. In 1914 it started its own research laboratory and has since then grown as a technological innovative company in many areas. Philips has been at the centre of inventions such as the CD, the DVD and the rotary electric shaver. But it also made breakthroughs possible in areas such as medical equipment and lighting solutions.

Philips is organized in three branches: Healthcare, Consumer Lifestyle and Lighting. The site in Drachten is part of Consumer Lifestyle and was established in 1950. Here they design and produce shaving and grooming products and test products like coffee makers and vacuum cleaners. About 2000 people work at this site. Over the last decades a substantial part of the production has been relocated to China and South East Asia, but in recent years Philips Drachten has managed to expand their production operations once again. This is possible due to the high level of automation within the factory.

Philips Drachten has a specific department that is responsible for the industrialization of new products; this is the department of New Product Introduction (NPI). NPI takes care of all new equipment and processes that are necessary for the production in Drachten. The research described in this thesis is carried out at this department.

1.2 Problem description

A new and innovative shaving product has been invented at Philips Drachten. The processes and machines that will be used for production are finished being designed right now and soon the production line will be set up. In this production line, only one type of product will be made and the line will be dedicated to producing this single product. Questions arise about where the machines should be placed within the factory, which part of the production should be make-to-stock and which part should be make-to-order, what size the buffers should have and how produced components should be transported through the factory.

In Figure 1, the material flow of the new product (minus the waste materials) is displayed. The processes that are needed to complete a product are displayed at the left hand side of this figure. The production starts with purchasing raw materials and some ready-to-use components. The metals are delivered in sheet form, rolled up on big reels. The metal is guided through a large generic press with specific tooling equipment which sequentially performs coining, bending, cutting and other cold forming operations. This all happens very quickly. In theory, more than six items can be produced each second. After possible deburring and washing, the components are ready for the next process.

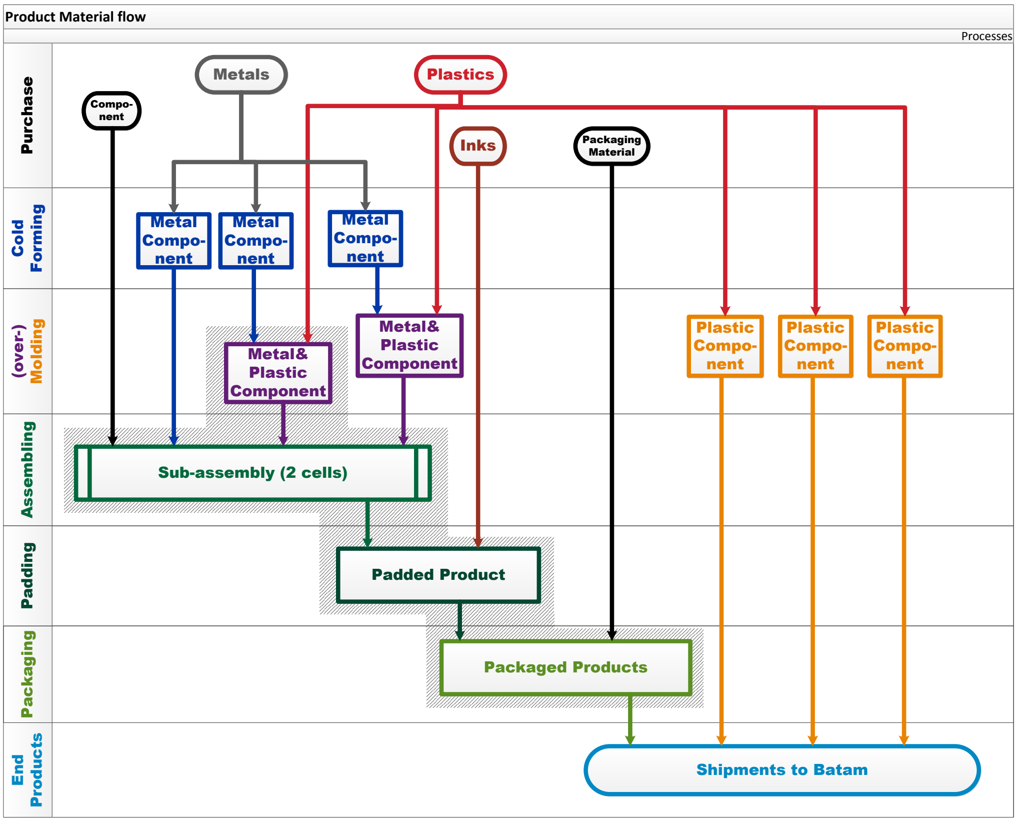


Figure 1. Schematic overview of the material flow of the production

To some of these metal items, plastic is added in a process called overmolding. This overmolding process, as well as the molding of solely plastic components, starts with different types of plastic granulates. These granulates need to be dried in an oven and are then poured in the molding machine. The granulates are melted in this machine. The molten plastic is injected into a mold with cavities and quickly cooled to harden the plastic; resulting in the desired shape of plastic component.

Once all components are produced or purchased, the assembly process can start. This is done by advanced robots that need to pick up the components and place them together with pinpoint accuracy. Some components are welded to each other and others are irreversibly snapped into each other. In this case two different assembly cells are required, where each cell is performing a distinct set of operations. During the sub-assembly four components are connected to each other, together forming a new type of components which is used in the final assembly operations later on. The semi-finished products are transported between the cells by means of carriers on a transportation belt. The replenishing of components is done by operators. These operators are also responsible for countering any failures that might occur.

After the first part of the product is assembled, some inks are stamped onto this product in a process called pad printing to increase the functionality and aesthetic value. It is then packaged for transportation to Philips Batam in Indonesia, which in this case is considered the customer of Philips Drachten. In Batam the product will be further assembled and packaged for commercial sales.

Dedicated machines are used for all processes, except for cold forming where the three metal components are (separately) made on the same machine. This means that machines can run for long periods of time. Machine failures are expected for each machine and a fraction of defected products is expected for each process. The method and type of carriers for transportation of each component can vary. These are all factors that influence the production rate and the production costs.

1.3 Research Scope

From the problem description it follows that the complete production needs to be set up and Philips Drachten still has many questions that need to be answered. The research that is required to answer all these questions in depth for every part of the production takes a lot of time. Time is limited however and for this reason the scope of this research is narrowed.

This research focuses on the final steps of the production line; indicated in Figure 1 by the grey box around the processes (one overmolding process, one assembly process, pad printing and packaging). From this moment on this entire sequence of processes is referred to as 'the assembly line'.

The most important factors for Philips Drachten are the production rate and the continuous working of the overmolding machine. The first factor is important, because customer demand needs to be met. The second factor is important, because the molten plastic within the overmolding machine starts to degrade when the machine is interrupted for too long.

Philips Drachten is most concerned with three design aspects. To improve the continuous working of the overmolding machine, Philips Drachten has already decided to place a buffer outside the assembly line (external buffer). This external buffer will decouple the overmolding machine from the rest of the assembly line. The first design aspect is the size of this external buffer. The second aspect is that the carriers that are used to transport the components are relatively expensive. One carrier costs about €500. So using fewer carriers would be beneficial. The third aspect is that in-line buffer space within the assembly line is limited due to the length of the assembly line. Philips Drachten wants to know how to divide this available space.

1.4 Research objective

The objective of this research is to provide Philips Drachten with recommendations on what size the external buffer should be, how many carriers to place in the assembly line and how to allocate the available buffer space among the machines. The recommendations will include:

1. Various combinations of number of carriers and buffer allocation that:
    a. yield a high production rate (throughput);
    b. yield a small amount of time in which the overmolding machine has to wait for empty carriers to be available or for full carriers to be able to leave the machine (starvation and blockage, respectively);
2. Insights on the effect of using fewer or more carriers in the assembly line;
3. Insights on how the production rate can be improved.

1.5 Research Questions

From the objective of this research the main research question that naturally follows is:

> *What is the effect of the number of carriers and the allocation of buffer places within the assembly line on the throughput of the assembly line and on the starvation/blockage of the overmolding machine?*

In order to answer the main research question the following sub-questions are answered:

What will the assembly line look like? – (Chapter 2)

> In order to optimize the assembly line, the first thing to find out is what the line will look like. This includes information on the kind of machines, the limiting factors for the buffer sizes, the sources of variances, the type of transportation between the machines and other relevant factors. The answer to this question will result in a top-level system overview. No data on expected processing times or distributions will be gathered here. The method used to answer this question is by conducting interviews with employees of Philips (process engineers, machine operators and the like) and the suppliers of the machines. Also, similar production lines that are currently in operation at Philips Drachten can be observed.

What literature is available that can help with the problem? – (Chapter 3)

Existing literature is studied to find out what research has already been carried out that can be used to help solve the problem. Naturally, the exact situation of the assembly line will not be available in the literature, but similar general modelling techniques are identified. These are used to model the different parts of the system and link them together.

How can the assembly line be modelled? – (Chapter 4, Sections 4.3 & 4.4)

From the system overview of the assembly line and the information gathered in the literature study, the model is built. At this point in the research some characteristics of the assembly line are needed, but not yet known (e.g. the kind of probability distributions of the service times of the machines). These characteristics are determined by answering the next sub-question.

What is the input data required for the model? – (Chapter 4, Section 4.5)

A substantial amount of parameters related to the machines and processes are needed in the model. Furthermore, data will be gathered to determine the maximum and minimum value of the buffer sizes and the total amount of buffer space available. For some processes, machines similar to those currently in use at Philips Drachten will be used. For these machines a lot of data is already available or can easily be extrapolated. Some machines however, are newly purchased and the parameters are collected with the help of the suppliers.

What design of the assembly line is best for Philips Drachten? – (Chapter 5)

Once the model has been built and all the input data has been gathered, the model is used to calculate the chosen performance indicators of the assembly line. A range of buffer allocations and number of carriers in the system are used to find the effect of these factors on the throughput of the system and on the starvation/blockage of the overmolding machine.

From these findings recommendations are made towards Philips Drachten in Chapter 6.

2 Lay-out of the Assembly Line

In this chapter the first sub-question of the research will be answered: What will the assembly line look like? The chapter starts off with a general overview of the assembly line in Section 2.1 and then continue to explain the individual parts more in-depth in Section 2.2.

2.1 Overview of the assembly line

The purpose of the assembly line is to convert components and other raw material into packaged products which can be shipped to the customer. In order to complete this conversion a product has to be processed at 17 individual machines divided over 5 production cells. A production cell is a big machine that consists of several smaller machines. A product has to pass all machines in series. Figure 2 shows a schematic overview of the assembly line.

The five cells are from left to right: the Overmolding Cell, the Assembly Cell, the Welding Cell, the Pad printing Cell and the Packaging Cell. In Figure 2 the positions of the machines are displayed by numbers. These numbers will be used throughout this thesis to refer to the corresponding machine. When there is no rectangle around a number, either components are added to the product or the product is moved to or from a transportation belt. When there is a rectangle around a number, operations are performed without adding or removing components. In Section 2.2 the operations happening at the machines are explained in more detail.

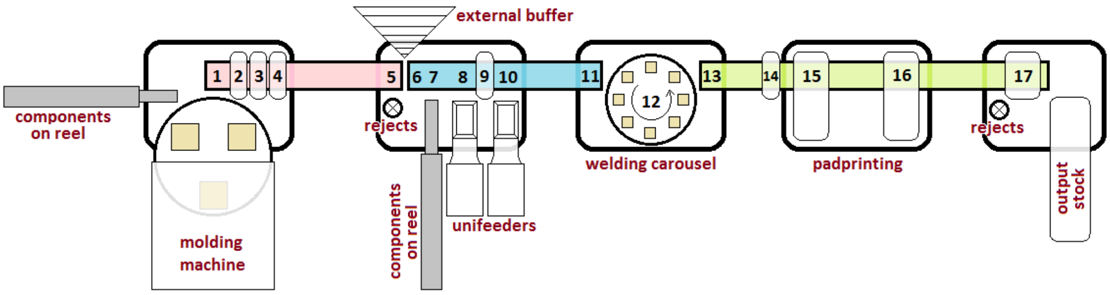


Figure 2. Schematic overview of the assembly line

Semi-finished products are transported between the machines by means of carriers on a conveyor belt. A carrier can transport several products at once. All machines can only work on one carrier at a time (machine 12 being an exception that will be explained in Subsection 2.2.3).The carriers are not fixed on the belt. This means that when one carrier stops for any reason, the carrier that is behind the first one will continue moving until it reached the first (stopped) carrier; this second carrier will then stop as well, because it cannot move through or pass the first carrier. This means that the transportation belt between two machines is a buffer space. When this buffer space is filled up with carriers, the machine at the start of the buffer space can no longer release its carriers and can no longer start processing on a new carrier; the machine becomes blocked.

There are three different carrier loops, displayed in Figure 2 by the red, blue and green areas. A carrier loop consists of two conveyor tracks right above each other and an elevator at each end of the tracks. Processing only happens on the higher track. The three carrier loops all have their own special carrier type. The types are; molding-, assembling- and printing-carriers. The carrier types are different, because they are designed to facilitate certain processes in the assembly line. The molding-carriers are designed to facilitate testing molded components (at Machine 2). The assembling-carriers are designed to facilitate sliding of several components into each other (at Machine 9). The printing-carrier is designed facilitate the pad printing process (at Machines 14, 15 and 16).

2.2 Cells and machines of the assembly line

The assembly line consists of five cells in series. All cells, machines and carriers, except the overmolding machine, are purchased through BWM (Bremer Werk für Montagesysteme). This supplier has provided Philips Drachten with almost all previous assembly machines and cells. In the following subsections the machine operations will be discussed per cell and the sources of variability will be identified.

All machines can experience breakdowns (machine failures). If this happens an operator will have to examine the machine to fix the problem. Because of this human interaction it is unsafe to let the remaining machines of a cell continue working. This means that if one machine breaks down, all machines that are in the same cell will stop working (cell failure). When such breakdowns occur and how long it takes to fix them is random. The exception is Machine 5, which is explained in Subsection 2.2.2. All processing times are fixed and constant unless mentioned otherwise. All values and probability distributions are presented in Chapter 4.

2.2.1 First cell: Overmolding Cell

The Overmolding Cell contains the first four machines. The most important machine here is the first one, which is the overmolding machine. This machine molds plastic around a piece of metal. When the processing is finished, the products are loaded onto a molding-carrier. The molding machine molds four products simultaneously and the molding-carrier to which the products are loaded also has four places.

The overmolding process is a delicate process. To get the liquid plastic, which is needed in the process, plastic granulates are melted. This takes some time. But once the granulates have melted, the plastic needs to be used as soon as possible, since the chemical structure of the plastic starts to degrade at high temperatures. If the plastic degrades too much it can no longer be used for production and needs to be expelled from the machine. After the expulsion production can resume again, but it will take some time to regain control of the process, resulting in a worse quality of products. This all is highly unwanted waste of time, material and quality and should be avoided as much as possible.

After all four products have been loaded onto a carrier, the carrier continues to Machine 2. At this machine the products are tested by shining a bright light at one end of the product and measuring the physical dimensions of the products. If a product does not pass the test at this point, the information that the products failed the test is stored on a chip which is embedded in the carrier. The information on the chip is read again at Machine 5, where rejected products will be disposed of. Processing at the intermediate Machines 3 and 4 still happens on rejected products.

At Machine 3 a QR-code is laser engraved onto each product. This code is read at Machine 4 as a test. If the code cannot be read the product failed this test. This information is again stored on the carrier's chip which is read at Machine 5. After Machine 4 the carrier leaves the Molding Cell and the carrier is transported to the second cell: the Assembly Cell.

A Fall Off Rate (FOR) is expected: a certain amount of products will not pass the test (fall off) and are thrown into a reject bin at Machine 5.

2.2.2 Second cell: Assembling Cell

The first element of the Assembling Cell is an external buffer. In this buffer products can be taken out of the system and temporarily stored. This might be necessary, because machines further down the line are subject to breakdowns. This will cause the machines in front to get blocked and, as explained in the previous subsection, the overmolding machine in the first cell should not stop producing. The external buffer makes sure this will not happen due to machine breakdowns happening at other machines than those in the Molding Cell. The external buffer works with the Last-In-First-Out rule.

Machines 5 and 6 are the unloading of the molding-carriers and the loading of the assembly carriers respectively. These two processes actually use the same robot, but since different carrier types are used, the distinction of the two machines is made. Also, the process at Machine 5 will not stop if any machine in the Assembling Cell breaks down. This is possible due to the placement of the robot at a safe position. At Machine 5 the products that were rejected at Machine 2 or 4 are picked up and thrown into a reject bin. There is no reflow, so all rejected products never return to the assembly line. If the product is not rejected it will continue to be processed by the assembly line. If a molding-carrier is fully unloaded, this carrier will return on the lower conveyor track to the overmolding machine in the Molding Cell.

Under normal operations the external buffer is not used and the products are picked up from the molding-carrier and directly placed on an assembling-carrier at Machine 6.The assembling-carrier can also hold 4 products. If, however, the assembling-carrier is already full or there is no assembly carrier present at Machine 6, the product is instead placed into the external buffer. On the other hand, it can happen that there is no molding-carrier to be unloaded at Machine 5, but there is an assembly carrier available at Machine 6 and there are products in the external buffer. In this case a product is picked up from the external buffer and placed onto the assembling-carrier. The above mentioned product displacements that the robot at these machines can facilitate are summarized by the arrows in Figure 3.

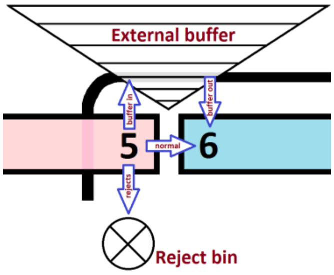


Figure 3. Product flow around the external buffer

Machine 7 cuts out metal components from a reel and places them on the carrier. The carrier will move to Machine 8 where another metal component is picked up and placed on the carrier. The assembling-carriers will carry three components per products now (making 12 components in total). At Machine 9 these components are slid into each other. This does not create a permanent connection; this permanent connection is made at the third cell (the Welding Cell). At Machine 10 another component is placed next to each product. After these processes the carrier leaves the Assembling Cell and is transported to the Welding Cell.

Machines 8 and 10 both add components to the carriers. This is done by the use of unifeeders. A unifeeder is a vision based pick and place solution by BWM. The supply of these components is done in bulk. The feeder pours some of the components onto a plate. Directly above the plate there is a camera which registers the position of the components. When a component is positioned correctly, a robot picks the component and places it on the carrier. When no component is positioned correctly, the plate will shake up and down a bit. This results in new positions of the components for the camera to register. Every now and then more components are poured onto the plate. Variability exists in the time for the components to be positioned correctly and be registered by the camera.

2.2.3 Third cell: Welding Cell

At this stage of the assembly line, four unique components for each product (i.e. a total of 16 components per carrier) have been added to the assembling-carrier. They were placed at the correct position, but the components are still not connected. This connection is made in the third cell where the components are welded to each other by means of laser beams. This happens in five consecutive welding steps. The welding steps are preceded by one loading step and followed by one unloading step, giving seven steps in total.

At Machine 11 the products (i.e. components) are unloaded from the assembling-carrier and placed onto the welding carousel (Machine 12). This carousel has eight positions evenly distributed on the outside of the carousel. Each position can hold one product and relates to one of the seven steps (plus one dummy position). Processing happens simultaneously at all positions where there is a product present. After processing, the carousel turns one position so each product reaches the next welding step. This means the processing time is determined by the step which takes the longest to complete. This time is constant and fixed.

At Welding Step 1 one product at a time is loaded from the assembling-carrier at Machine 11 onto the carousel. Since there are four products on an assembling-carrier it takes four steps to unload the carrier. When an assembling-carrier is fully unloaded, it leaves the Welding Cell and returns to Machine 6 of the Assembly Cell.

At Steps 2-6 welding takes place and at Step 7 the product is loaded onto a printing-carrier at Machine 13. This carrier can again carry four products, so it takes four steps to load a carrier. When a printing-carrier has been fully loaded it can leave the cell and can continue to the fourth cell: the Pad printing Cell.

It could happen that a product is ready to be unloaded from the carousel at Step 7, but there is no printing-carrier available at Machine 13, or the printing-carrier at Machine 13 is already full and it cannot leave, because it is blocked by carriers in front of it. If this happens, the product cannot leave the carousel at Step 7 and the entire carousel stops. All processing at Machines 12 and 13 is halted until a new (empty) carrier can be processed. This also means that the assembling-carriers at Machine 11 will stop being unloaded. So the second and third carrier loops are tightly coupled by this welding carousel. This is in contrast with the first and second carrier loops which are decoupled by the external buffer.

2.2.4 Fourth cell: Pad printing Cell

In the fourth cell inks are added to the product. For the ink to be able to stick to the products, the products need to be completely clean. So first, Machine 14 cleans the products thoroughly by briefly exposing the products to a hot flame. Machine 15 then stamps functional ink onto the product. The ink is dried by infra-red light, which works while the carriers are moving on the conveyor belt towards the next machine. This is Machine 16 and it stamps aesthetic ink onto the products. The ink is again dried by another source of infra-red light while it is moving to the end of the Pad printing Cell.

2.2.5 Fifth cell: Packaging Cell

The fifth and final cell adds a little oil to the products and performs functional tests on the products. If the product fails the test, it is put into a reject bin. A certain fall off rate is expected here. Most products will pass the tests and are packaged, ready to be shipped to the customer. The testing and packaging is done on a carousel. The positions on this carousel can hold four products. The printing-carrier can already leave once it has been unloaded. This unloading happens at Machine 17. When a carrier is unloaded it returns to Machine 13 of the Welding Cell.

2.3 Summary

In this chapter the lay-out of the assembly line has been presented. By doing so the research question has been answered: What will the assembly line look like?

The assembly line has 3 carrier loops, each with their own carrier type. For each carrier type the effect of using a certain number of these carriers will have to be researched.

Between the first and second carrier loop an external buffer will be placed in order to decouple the overmolding machine from the rest of the assembly line. The size of this external buffer still needs to be determined.

Almost all processing times at the machines are fixed and constant. Only at Machines 8 and 10 variability exists. There also exists variability in the occurrence of breakdowns and the time it takes to repair a production cell. A third source of variability is the fall off rate at the Molding Cell and the Packaging Cell.

There are transportation times between machines. The buffer space in between machines is limited.

3 Literature Review

In this chapter the second research question will be answered: What literature is available that can help with the problem? The question is answered by studying existing literature related to the problem and looking for methods of solving the problem. In Section 3.1 the problem is classified. In Section 3.2 the approaches of solving this problem are discussed. In Section 3.3 the theory relating to using simulation is presented.

3.1 Problem classification

The first step in the literature study is to classify the problem. Once a classification has been made, more direct searches for solving the problem can be made.

There are many different types of manufacturing systems and several ways of modelling them. To allow for variability in processing times a manufacturing system can be modelled as a queueing network which can be analytically evaluated (Zijm, 2012) or as a network which is evaluated by means of simulation (Law, 2006). Classification for these networks depends on the following factors:

- Type of production
- Routing of jobs
- Type of processing and distribution of processing times
- Control of workload (open/closed system)
- Reliability of machines
- Synchronization of the system
- Types of products
- Batch forming
- Buffer limitations

Production can either happen with discrete or continuous manufacturing. The products that are produced can be counted and uncompleted products have no value. *The production of the assembly line at Philips Drachten is discrete.*

In the assembly line that will be placed at Philips Drachten all products start at the beginning of the assembly line and follow a set serial path to the end of the line. *The assembly line is a serial network*.

The processing times are mainly constant, for some machines variability exists due to the use of unifeeders. *The assembly line at Philips Drachten consists of machines with general service times*.

The products are moved through the assembly line by means of carriers. Once the products are removed from the carrier, the carrier returns to the beginning of its loop. *The assembly line at Philips Drachten is a network that consists of several closed queueing sub-networks in series*.

Machines can break down at any moment and it will take some time to repair a machine. *The assembly line at Philips Drachten consists of unreliable machines*.

The first cell is a bit faster than the 4 other cells, but this is designed to compensate for a bigger expected FOR after the first cell. The machines of the last four cells are all designed to have about the same processing time for one carrier. However, the machines are not coupled and can work in an independent way on different carriers. *The assembly line is a semi-synchronized system*.

The assembly line only works on one type of product and changeovers never occur. *The assembly line at Philips Drachten is a single class network*.

Due to the use of carriers, move batches exist in the network. However, processing at a machine happens to all products on the carrier. For this reason a carrier can be taken as the unit for processing and batch forming/decomposing can be omitted at most machines. Only at the welding unit (in the third cell) the products are processed individually; in this case the forming and decomposing of batches can be considered as an independent processing step. *The assembly line at Philips Drachten has one cell where batches are decomposed and formed*.

The distance of the transportation belt on which the carriers move is limited. The carriers have physical dimensions and cannot be stacked. *The buffers have finite size.*

So the classification of the assembly line at Philips Drachten is:

A single class multi-loop closed manufacturing system with unreliable machines and finite buffers.

3.2 Approaches for solving the problem

Queueing networks can be solved analytically when the problem is not too complex. For very simple problems this method gives exact results, but most of the time approximations have to be made. A big advantage of this approach is the speed at which solutions are found. As explained by Zijm (2012), a simple queueing problem is a problem where all time dependent factors have the memoryless property (i.e. the remaining time it takes to complete an action is independent on the time that has already passed). This means that all processing times, Times Till Failure, Times To Repair, etc. have an exponential distribution. Also, the buffers between the machines should be of infinite size. In the case of the assembly line at Philips Drachten however, this is not the case and the problem is too complex; too many approximations will have to be made to get reliable results. Even the constant processing times for most of the machines increases the complexity a lot.

Methods for approximate evaluation exist for dealing with a high degree of complexity, such as the method of Gershwin (1986) for tandem queues with finite buffers, or the method of Li et al. (2009) for two connected carrier loops. These methods only apply on the standard problems, but could be extended to deal with the problem of the assembly line at Philips Drachten. However, to validate this extended model the results would have to be compared to results coming from the real assembly line or results of a simulation study. The real assembly line does not exist yet and to do a simulation study next to the analytical approach would take up too much time.

When the analytical approach is too complex it is beneficial to consider simulation (Li et al., 2010). The drawback of simulation is that it takes longer to get reliable results in terms of computational times. A big plus is that changes to the system can be incorporated quickly. Especially since the assembly line is still in the design phase, this is very important. These changes happened a lot during the time that this research was conducted and I expect minor changes are still happening right now at Philips Drachten. For this reason simulation is chosen to solve the problem.

3.3 Using simulation models

By using a simulation model of the assembly line, data can be generated to estimate the performance of the assembly line (Law, 2006). A scenario (consisting of a set of input parameters) for a simulation model can be changed and the results can easily be compared. From this comparison an optimal or desired scenario can be chosen. Testing these scenarios on the actual assembly line is expensive and will take a lot of time. Also, the assembly line is under development at this point, so this is not possible.

3.3.1 Method of using simulation models

Using simulation to estimate a system's performance can be done in three phases: problem definition, model construction and experimental design (Mes, 2012). A summary is given in Figure 4. During the problem definition phase (presented in Chapter 4) the problem is defined and a plan is made to conduct the simulation. At the end of the problem definition phase a project specification has been made. The project specification is presented in Chapter 4 and consists at least of the following points:

Problem introduction and problem goals, expected contribution and results, model description, data requirements and collection method, time planning, cost estimate.

In the model construction phase (presented in Chapter 4) the model is built. The system parameters are gathered. The model is programmed, verified and validated. At the end of the model construction phase a working and valid simulation model exists that can be used to test different scenarios.

In the experimental design phase (presented in Chapter 5) the different scenarios that are to be tested are determined. These scenarios are put into the model and the model is run. The results from running the model are analysed and an optimal or desired scenario is chosen.

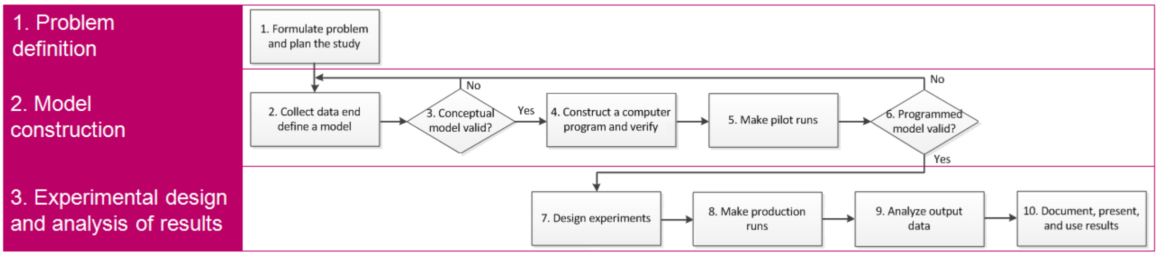


Figure 4. Phases of conducting a simulation study (adaptation from: Mes, 2012)

3.3.2 Types of simulation models

To classify the different types of simulation models Law (2006) uses three dimensions:

- Static vs. Dynamic: when a model is static it only concerns the system at a fixed time; when a model is dynamic it shows how the system evolves over time.
- Deterministic vs. Stochastic: when a model is deterministic no randomness is induced; when a model is stochastic one or several sources of randomness are modelled.
- Continuous vs. Discrete: when a model is continuous the change of the system state is calculated continuously; when a model is discrete the system state changes at certain intervals.

Several types of simulation models can be used:

- Discrete-Event Simulation
- Continuous Simulation
- Combination of Discrete and Continuous Simulation
- Monte Carlo Simulation
- Spreadsheet simulation (for small simple problems)

From the main research questions the main performance indicators are identified. These are the throughput of the assembly line and the blockage/starvation of the overmolding machine. These indicators are measured over time and looking at a fixed point in time would generate no usable data. *This means the model should be a dynamic model.*

Random failures of the production cells and the processing times of the machines with unifeeders have been identified as sources of variability in Chapter 2.*This means the model should accommodate stochastic elements.*

It is not necessary to model changes in the system state continuously. Changing the system state only at discrete events will be much faster. *Discrete event models can be used.*

3.3.3 Simulation model design

The assembly line is not simple enough for spreadsheet simulation. Based on this and the classification mentioned in the previous chapter, the simulation type I will use is Discrete Event Simulation. The main idea incorporated by these kinds of simulations is that events happen only at discrete points in time. The time in between two subsequent events is of no interests and is skipped completely. This means that the change in the system state is only determined when an event happens. All events are stored in an event list. The model jumps from event to event in the order at which the events happen. Each event can generate future events.

Simulation models could potentially run for an infinite amount of time. A stopping criterion needs to be set that indicates when the model should stop. Criteria can for instance be that a certain amount of time (simulation time or real time) has passed, or a certain amount of products has been produced.

Running a stochastic model only once will only provide limited results. The run could have been an extreme case, or it could be a very average case. Without further research there is no way of knowing this. And even if it is an average case, information on the variance of the outcome is desired. For these reasons the model is run several times for the same scenario, but with different random numbers. The random numbers will be statistically independent, ensuring also the statistical independence of the outcomes of different runs. The more times this is done, the greater the statistical significance of the outcome. However, it will also increase the time it will take to come to an outcome. The minimum amount of runs that should be made per scenario can be calculated by allowing a certain relative width of the confidence interval of the performance measures (Law, 2006).

The minimum amount of runs per scenario is determined by finding the smallest number of runs n for which the following formula holds:

$$t_{n-1,1-\alpha/2} * \frac{1}{\sqrt{n}} * \frac{s_{X_n}}{|\bar{X}_n|} \leq \frac{\gamma}{1+\gamma},$$

where X_n is the set of results for a performance measure (e.g. the amount of products that the assembly line produces) when n runs are performed. $\bar{X}_n$ is the average value of the performance measure and s_{X_n} is the empirical standard deviation, $t_{n-1,1-\alpha/2}$ is the two-tailed critical value of the student-t distribution with n-1 degrees of freedoms and a significance level of α and γ is the relative error which is allowed in the results. For the significance level (α) 5% is used. The relative error (γ) allowed is 5%.

3.4 Conclusion

The assembly line has been classified as: *a single class multi-loop closed manufacturing system with unreliable machines and finite buffers*.

The assembly line is too complex to be modelled analytically, mostly because the processes of the system do not have the memoryless property and buffer space between the machines is finite. A lot of assumptions will have to be made and even then the model that is created will be very problem specific and changes to the assembly line cannot be incorporated easily. For this reason the assembly line will be modelled using simulation.

Different types of simulation models can be used. A choice has been made to use Discrete Event Simulation, because this is a fast simulation type that can cope with the complexity of the problem. To use this simulation the following phases will be completed: *problem definition (in Chapter 4), model construction (in Chapter 4) and experimental design (in Chapter 5)*. Stopping criteria and a number of runs per scenario will have to be determined.

4 Modelling the Assembly Line

In this chapter the third and fourth research question are answered:

How can the assembly line be modelled?

What is the input data required for the model?

This chapter deals with the first and second phase of the phases presented in Subsection 3.3.1: problem definition and model construction. The third phase (experimental design) will be presented in Chapter 5.

First the project specification is presented in Section 4.1. In Section 4.2 the model assumptions are presented. Then, the general dynamics of the model are presented in Section 4.3. This is followed in Section 4.4 by an in-depth explanation of the different modules of the simulation model. After this, the input data for the model is presented in Section 4.5. The model is validated in Section 4.6. In Section 4.7 the type of data that the model will generate is presented.

4.1 Project specification

The deliverable of the problem definition (the project specification) is presented here. Time and costs are not relevant to specify the project and are omitted.

4.1.1 Problem introduction and problem goals

The simulation will be used to find an answer to the main research question of this study. The effects of the amount of carriers and the allocation of buffer space in the assembly line on the throughput and on the blockage/starvation of the overmolding machine will be determined. After analyzing these effects, possible improvements to the current design of the assembly line are tested.

4.1.2 Expected contribution and results

Based on the results of running the simulation, recommendations can be made. These results and recommendations will be reported. The simulation model itself is also a contribution, as it can be used by Philips Drachten to include or test future changes to the assembly line. A manual will be made for employees of Philips Drachten on how to use and adapt the model. Also, the model will be explained to employees responsible for the design aspects of the assembly line.

4.1.3 Output data requirements and collection method

The required data will be collected by gathering data of the system state of the model. Results from different scenarios can be compared by using a paired-t test. A full explanation of this test is given in Appendix B. The main idea behind this test is that the simulation runs of one scenario are paired to the same simulation runs for another scenario. The difference in results of these paired runs are determined. This difference is a random variable on its own and when the mean difference is larger than zero (with a 95%-confidence interval), then one scenario is considered to be better than the other scenario.

Averages and confidence intervals can be calculated to see if the assembly line will live up to the expectations set by Philips Drachten (which can be found in Subsection 4.7.1). The results will need to be statistically relevant with a significance level of 5%.

4.2 Assumptions

To simplify the model the following assumptions can be made:

All variable processing times, failures and repair times are assumed to be statistically independent.

It is assumed that all components and other materials are always readily available (i.e. there are no stock-out occasions). This assumption holds, because the operators at the assembly line are trained to facilitate this.

The first cell is considered to be the load/unload station and it is assumed new production orders are always available during the entire shift. This assumption holds, because production is planned weekly. Either the weekly target has been met and a shift will not start, or the target has not been met and production continues for an entire shift.

Machines 5 and 6 are assumed to be separate machines. In reality these machines are the same robot as explained in Subsection 2.2.2. By modelling these processing steps of unloading a molding-carrier and loading an assembling-carrier separately, the model is simplified. This could result in a very small desynchronization of these machines; which in return results in very small offsets in the process completion times at Machines 5 and 6. This offset is at most $\frac{1}{2}\frac{processing\ \ time}{products\ \ per\ carrier} = \frac{1}{8} processing\ time$ and does not cumulate.

The buffering of carriers is simulated using vertical queues (Bell, 1997). In real production lines a carrier cannot continue its transport if the in-line buffer space in front of the carrier is already full. The transport will be interrupted and resumed once the carrier can move again. In the simulation however, this is not considered, since the dynamics of the system do not change due to this interruption. The carrier can still only be taken into service when it is the first carrier in the buffer and the machine is ready for a new carrier. The transportation belt still has a maximum buffer size, so blocking is still possible if this buffer is full. This assumption does not influence the reliability of the model, but it does mean that no performance measures related to this transport interruption can be gathered.

The external buffer between the molding-carrier loop and the assembling-carrier loop is modelled to be of infinite size. In real life a limit exists on the size of this external buffer. Data is gathered on the dynamic behaviour of the amount of products present in this buffer. Based on this data recommendations can be made on what size the external buffer should be and how the buffer should be managed when it is full.

The warm-up period is included in the results, because shifts start with an empty assembly line (with a possible exception being the initial stock in the external buffer). The assembly line will be stopped and restarted regularly, so Philips Drachten is not interested in the long term performance, but in the performance of the entire shift. The assembly line is stopped for two reasons in particular. The first is to perform maintenance. This decreases the probability of machine failures. The second reason is to replace some of the printing-carriers. These carriers will get dirty because of the pad printing process. When too much ink has accumulated on the carriers, the products will get dirty and will have to be disposed of.

4.3 The model in general

No software is currently used at Philips Drachten to simulate the production operations. Also, I have no personal experience with simulation software that I am allowed to use to solve this problem. For these reasons I decided to build a simple discrete event simulator myself using Matlab. The Matlab version used is 2010b. Philips Drachten has licenses to use Matlab and a lot of the employees are well experienced with the program. The model that I build can be passed on to these employees. They will be able to use the model and adapt it if some aspects of the assembly line change.

4.3.1 State of the system

Variables are used to keep track of the state of the system. This state includes if a machine is broken, the amount of carriers in a machine's buffer, if a machine is working on a carrier, if a machine is blocked, the amount of products in the external buffer and if a carrier has finished its transportation time (from one machine to another).

4.3.2 Event lists

The events at which the system state can be changed are tracked using event manager lists. These are lists of events specifying the time at which the event is to happen, the type of event, the place of the event and other data relevant for dealing with the event. For practical purposes three types of event manager lists are used: one for cell events (affecting several machines at once), one for standard machine events (affecting carriers at the machines) and one for welding machine events (affecting the operations at the welding cell (3rd cell). The main reason for this distinction is the different types of data needed for handling these events and the use of the order of certain types of events. All three lists need to be searched for finding the event that is about to happen next. The welding machine event list is always sorted in order of increasing runtime. The cell event list is always sorted, first in order of increasing cell number and then in order of increasing runtime; this means each failure event in the list is always directly followed by its subsequent repair event. The list for standard machine events is not sorted. This choice is made, because the computational time it takes to sort this event list is greater than the time it takes to find the minimum runtime in the event list (i.e. next event).

4.3.3 Inducing randomness

To cope with the variability of the assembly line pseudo random numbers can be used (Gentle, 2003). Pseudo random numbers are used to simulate variability in cell failures and repairs, fall off rates and fluctuations in processing times. The pseudo random numbers are generated using Matlab's random number streams. The type of generator I used for the streams is the 19937-MersenneTwister; it is readily available in Matlab. Each stream is reset at the beginning of a run and seeded with a different number. This makes sure different random numbers are used for each run of a scenario. The pseudo random numbers generated here lie between 0 and 1. In order to convert these into usable values (for variable processing times, times till failure, times to repair and products falling off), the pseudo random number is used as input in the inverse cumulative distributions of the respective random variables. For instance: if the Fall Off Rate is 5%, then for each product that is tested, a random number is generated. If this random number is smaller than 0.05, then the product falls off; if the random number is bigger than 0.05, then the product does not fall off.

When another scenario is tested, the same seeds (and thus the same random numbers) are used. This makes it easier to compare how different scenarios react in relation with each other. The seed numbers that I use can be found in Appendix A.

4.3.4 Running the simulation model

A simulation run starts with the initialization of the system. Events are then handled in order. Each event can add new events. This is continued until the stopping criteria are met (these criteria are presented in Subsection 4.5.1). A new run is initialized and the process of handling events is repeated. Once a certain number of runs (determined in Subsection 4.5.1) is completed a new scenario is set and the runs repeat themselves. All the scenarios that need to be tested are set before running the model (i.e. the program uses run batches). This means that once the simulation starts running, no more input from the user is required until all scenarios have been simulated. This in turn means that the simulations can be run outside of office hours.

4.4 Modules of the simulation

4.4.1 Runplanner

The simulator is built around one main script called the runplanner. From this script several other scripts are called in sequence. An overview of the scripts is given in Figure 5.

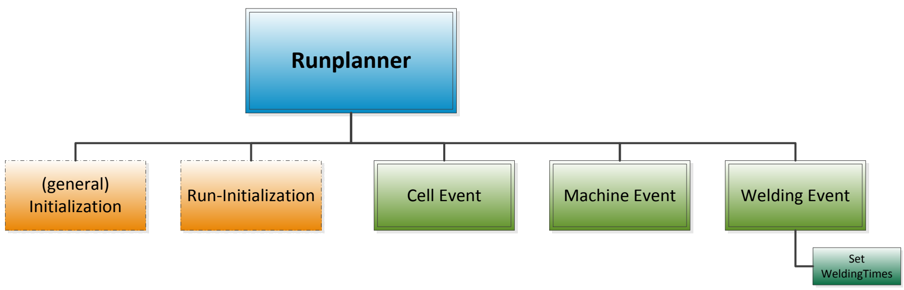


Figure 5. Overview of the simulator

The procedure of the runplanner can be summarized as follows:

1. Set system parameters by calling the general initialization script.
2. (Re-)set runtimer.
3. Set the specific scenario/run parameters and initialize the event managers.
4. Find the next event about to happen and increase runtimer accordingly.
5. If the runtimer exceeds the specified run length: go to Step 8.
6. Handle the event found in Step 4.
7. Return to Step 4.
8. If more scenarios are to be carried out: return to Step 2.
9. Clear up computer memory by releasing certain variables and constants.

4.4.2 Initialization

The general initialization script is run once, at the beginning of the simulation. The values for the parameters that are set in this script are presented in Section 4.5. It tasks are:

- Set general run parameters:
    - the length of one run (simulation time), the amount of runs per scenario.
- Set cell parameters:
    - MTTF, MTTR, FOR.
- Set machine parameters:
    - type of carrier handled by machine, cell to which the machine belongs, processing time for one carrier, transport time from the previous machine, size of the buffer, index of the next machine, index of the previous machine.
- Set carrier parameters:
    - amount of carriers, number of products carried by the carrier.
- Set initial scenario.
- Prepare result arrays:
    - machine status, production, rejection, stock in external buffer.

4.4.3 Runinitialization

At the beginning of each individual run, the run initialization script is called. It tasks are:

- Check if all the runs for a certain scenario are completed. If this is the case the parameters for the next scenario are set and the runcounter is reset.
- Update the runcounter and runnumber.
- Set all random number streams.
- Reset the system state.
- Reset the event handling lists and set first event at simulation time 0.
- Set all failure and repair events for the entire run.
- Set first processing events.

4.4.4 Handling events

Once a run is initialized, the simulation run can start. Events are handled in the order they occur. During the handling of each event, new events can be added to the event manager lists. Once the handling is complete, the event is deleted from the list and the next event about to happen will be handled. The events that can occur and a small explanation are given below. A complete overview of how the events work can be found in Appendix C.

Cell Events (for all 5 cells):

- **Cell breaks down–***production stops at all machines within the cell*
- **Cell is repaired–***production continues at all machines within in cell*

Standard Machine Events (for machines 1-11 & 13-17):

- **Transportation finished –***a carrier has arrived at the machine*
- **Processing finished–***the machine has finished processing a carrier*
- **Machine unblocks–***the carrier that blocked the machine can leave*
- **Start service –** *processing can start on a carrier at this machine*
- **Gather data –***this event has no influence on the system state, but is a trigger to collect data*

Welding Events (for Machine 12):

- **Assembling-carrier arrives –***new products arrive at the welding cell*
- **Assembling-carrier is unloaded –** *the assembly carrier is empty*
- **Product at end of carousel –** *a product is ready to be loaded onto a printing-carrier, if no carrier is there the machine becomes blocked*
- **Printing-carrier is full –** *a printing carrier has been fully loaded*

4.5 System parameters

The general initialization script sets all the necessary system parameters for the model to be able to run (see Subsection 4.4.2). This Section will show the values of these parameters and how they have been determined.

4.5.1 General run parameters

Length of a run: production at Philips Drachten happens in shifts. One shift lasts for 8 hours. So the time simulated for each run will be 8 hours which is 28800 seconds. As explained in Section 4.2, the warm-up behaviour is included in the results.

Amount of runs per scenario: a method for calculating the minimum required number of runs was presented in Subsection 3.3.3. By doing an initial simulation run and taking the amount of products produced per shift as the performance measure, the minimum number of runs is calculated to be 12. The point of limiting the number of runs is reducing computational time, but each run only takes about 7 seconds, so time is not really an issue. 100 runs per scenario are taken for the number of runs. Using the formula in Subsection 3.3.3, this results in a relative error (γ) of about 1.5%. The calculations for these numbers can be found in Appendix A.

4.5.2 Cell parameters

Since the cells do not actually exist yet; estimations will have to be made on the parameters. This is done by consulting employees at Philips Drachten and BWM who have experience with the production processes, machines and cells. Also, similar production lines are studied which are currently in use at Philips Drachten; this includes looking at data gathered by the factory information system and by going to the work floor to observe the production lines that have elements similar to this assembly line. For some parameters Philips Drachten wants to know the effect if these values are improved.

Fall-Off-Rate (FOR): In the first year of production the FOR after the molding process is expected to be 22%. The FOR at the end of the production line is expected to be 5%. These values come from numbers set by the project leaders at Philips Drachten.

Mean Time Till Failure (MTTF) & Mean Time To Repair (MTTR): For the first cell with the overmolding machine the MTTF is expected to be 3600 seconds (1 hour) and the MTTR is expected to be 400 seconds (6 minutes 40 seconds). This is established by talking to the molding experts who are responsible for the industrialization of this production step. The values are chosen to give a process availability of 90%. This process availability is set by management and is based on previous experiences with introducing new production lines.

For the remaining cells 40 weeks of available data from the factory information system is studied. Similar cells show MTTF values between 1000 and 1500 seconds and MTTR values between 80 and 300 seconds. Based on these values the MTTF and MTTR values of the production cells of the simulated assembly line are estimated to be 1350 seconds and 150 seconds respectively. This gives a process availability of 90%, which is again set by management. These estimations are justified because every cell will have a different behaviour, but this behaviour can only be truly estimated by studying failure times and repair times of the actual cells. Once the real assembly line is in use, the real behaviour can be simulated. For the same reason I assume Cells 2, 3, 4 and 5 all have the same probability distributions for the Time Till Failure (TTF) and the Time To Repair (TTR). This has been discussed with and agreed upon by experts at Philips Drachten.

The type of distribution is determined by running goodness-of-fit tests on the data from the factory information system at a cell level. The available detailed data on a cell level, which is needed to perform these tests, is however limited to one week. The following distribution types are tested: Weibull, gamma, exponential, lognormal, generalized Pareto with 0 threshold and hyper-2 exponential with balanced means. The goodness-of-fit tests used are the Chi-squared test and the Kolmogorov-Smirnov test of Matlab (MathWorks, 2012). The tests and the results are presented in Appendix D. For the overmolding cell no data is available on failure and repair times and assumptions will have to be made.

For the TTF, the only distribution that passed the test is the gamma distribution. This is one of the distributions that are widely used for failure times (Kalbfleish & Prentice, 1980). This is the distribution that will be used in the simulation for the last four cells of the assembly line. Based on this distribution, the distribution for the Molding Cell is also assumed to be a gamma distribution with the same shape parameter, but with a different scale.

In the simulation model I use TTF ~ Gamma(0.365 , MTTF/0.365). These distributions are chosen for the times till failure:

$$TTF_{cell1} \sim Gamma(0.365 , 9863)$$
$$TTF_{cells2\text{-}5} \sim Gamma(0.365 , 3700)$$

For the Time To Repair (TTR) the only distribution that passed the test is the lognormal distribution. This distribution is widely used for repair times (Ananda & Gamage, 2004)). This is the distribution that will be used in the simulation for the last four cells of the assembly line. Based on this distribution, the distribution for the Molding Cell is also assumed to be a lognormal distribution with the same coefficient of variation (implying the same variance parameter of the lognormal distribution).

In the simulation model I use TTR ~ Lognormal($\ln(MTTR) - \frac{1}{2} \cdot 1.0641^2$, 1.0641). These distributions are chosen for the times to repair:

$$TTR_{cell1} \sim Lognormal(5.4253 , 1.0641)$$
$$TTR_{cells2\text{-}5} \sim Lognormal(4.4445 , 1.0641)$$

Cell	Cell 1:	Cell 2:	Cell 3:	Cell 4:	Cell 5:
MTTF (seconds):	3600	1350	1350	1350	1350
MTTR(seconds):	400	150	150	150	150
FOR:	22%	-	-	-	5%

Table 1. Parameters of the production cells

4.5.3 Machine parameters and variables

As for the cells, the machines do not actually exist yet; estimations will have to be made on the parameters. This is done by consulting employees at Philips Drachten and BWM who have experience with the production processes, machines and cells. Also, similar production lines currently in use at Philips Drachten are studied; this includes looking at data gathered by the factory information system and by going to the work floor to study the production lines. A summary of these parameters is given in Table 2.

Processing Time (PT): The average processing times per carrier are gathered by talking to the experts responsible for the industrialization of the respective processes. All but two machines have deterministic constant processing times. The two machines which have variability are the machines in the second cell which involve picking and placing components with the unifeeder system of BWM. The variability is estimated by looking at current production lines and discussing the results with experts at Philips Drachten and BWM. Both machines have the same discrete probability distribution: with a probability of 1.2% the PT is 10 seconds, with a probability of 97.7% the PT is 12 seconds, with a probability of 1% the PT is 14 seconds and with a probability of 0.1% the PT is 16 seconds. This relates to the amount of times the plate of the unifeeder system has to shake during processing (0, 1, 2 and 3 times respectively).

Transport Time (TT): The transportation time between two machines is calculated by dividing the distance between the two machines by the speed at which the transport belt moves. The speed of the belt is constant and the distance between machines is fixed during a simulation run. This means all transportation times are constant. The transportation time of a machine is defined as the time it takes a carrier to move from the previous machine to the machine itself.

Buffer size: Within the cells there is a fixed number of carrier positions, including buffer space. Between the cells the available buffer space depends on the distance between the cells and the size of the carriers. The size of each of the carriers is 12 centimetres. A choice has already been made to set the distance between two succeeding cells to 1 metre, but small changes in these distances are still possible. This means that the available buffer space is $\frac{1\ m}{12\ cm/carrier} \approx 8$ carriers in between two succeeding cells. The Molding Cell has a turn in the carrier loop's transportation belt resulting in space for extra carriers before Machine 5. The Printing Cell is a bit extended towards the Welding Cell, taking away 2 buffer places before Machine 14. When a carrier arrives at the last machine of a carrier loop it has to return all the way back to the first machine in the loop. This causes the higher amount of buffer space before Machines 1, 6 and 13.

The assembly line cannot be made any longer than the current design (i.e. the Molding Cell and the Packaging Cell cannot be moved further apart), but the relative distance in between the cells can still be altered; there are three possible movements. The Welding Cell can be moved 0-25 centimetres towards the Assembling Cell, the Printing Cell can be moved 0-25 centimetres towards the Packaging Cell, or the Welding Cell and Printing Cell can together be moved 0-25 centimetres towards the Packaging Cell. The changes in buffer space that are possible due to these movements are all simulated and can be found in Section 5.2.

Machine m:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
PT_m (s):	10	10	10	10	8	8	12	12*	12	12*	-	3	-	12	12	12	12
TT_m (s):	10	2	2	2	20	16	2	2	2	2	6	0	18	4	6	2	6
$Buffer_m$:	16	1	1	1	24	20	1	1	1	1	8	-	45	6	1	6	8

** mean values of variable processing times*

Table 2. Parameters of the processes and logistics of each machine of the assembly line

4.5.4 Carrier parameters and variables

Number of carriers: the number of carriers for each of the three carrier loops is still to be decided. For the first carrier loop it can be calculated exactly how many carriers are needed to make sure a carrier is always available at the overmolding machine. This is possible, because all processing times are constant and the unloading machine at Cell 2 (Machine 5) is assumed to be unaffected by breakdowns. The number of molding-carriers is determined by:

$$\left\lceil \frac{1}{\max\left(PT_{m \in loop}\right)} * \sum_{m \in loop} (PT_m + TT_m) \right\rceil ,$$

where m is the machine number and $loop$ is the set of all machines inside a carrier loop. The second factor of this formula (with the summation sign) is the time it takes for one carrier to go through the entire loop uninterrupted. The first factor contains the processing time of the slowest machine. The outcome of multiplying these factors is the amount of carriers, which this slowest machine can work on before the first carrier that the machine started to work on returns. Since only an integer amount of carriers can be placed in the system, this number should be rounded upwards. The number of molding carriers calculated with this formula is 9.

The number of assembling-carriers and printing-carriers are still to be determined by this simulation study.

Products per carrier: The number of products that each carrier can hold is designed to be 4 for each type of carrier.

4.5.5 External buffer

Initial amount of products in the external buffer: this number is still to be determined A first choice is to make this number very large (i.e. 10000) to make sure the external buffer is never empty. After running the model for some scenarios a more realistic number can be determined.

4.6 Model validation

The outcomes of the simulation model should give a good representation of reality. To see if this is true the model is validated.

4.6.1 Comparison to existing production lines

Because I created the entire discrete event simulation model from scratch using Matlab, it is not straightforward that the model completely resembles a real production line. To prove this, simulation results are best compared to real life results. But since the real assembly line is still under development, no real data is available to validate the model. Because of this, the simulation model is adapted to represent a similar existing production line at Philips Drachten that is currently in use.

The real production line in this case has an average production rate of 750 products per hour with a 95% confidence interval of [731-768]. The simulation model gives an average production rate of 742 products per hour with a 95% confidence interval of [725-758]. The data of the real production line is then compared to the results from the model by using the Kolmogorov-Smirnov test and the two sample t-test (MathWorks, 2012). Both tests do not disprove that the simulation model gives the similar results than the real production line. The results and the statistical tests to support the findings can be found in Appendix E.

I conclude that the (altered) simulation model I created can resemble a real production line. This is not proof that the model resembles the assembly line that will actually be used. To this end the extra features of the future assembly line (i.e. the external buffer and the automated coupling of carrier loops) are discussed with experts. This is presented in the next subsection.

4.6.2 Expert opinion

The model is extensively discussed with expert from Philips Drachten and BWM. Based on their recommendations the model has been slightly adapted to give a better representation of the future assembly line. These adaptations are already incorporated in the model presented earlier in this chapter. The results of the simulation have also been discussed with experts from Philips Drachten and BWM. The experts concluded that the results are a good expectation of how the assembly line will perform once it is in operation.

4.6.3 Model limitation

One limitation of the model has been identified: if a carrier loop is saturated with carriers, the simulated production line will almost immediately come to a stop. This is because all buffers between the machines are always full and no trigger is programmed that allows all machines in a carrier loop to simultaneously release the carriers they are working on. There is no need to implement this trigger, because Philips Drachten never saturates any carrier loops.

4.7 Data gathering

This section explains how the simulation model is used to generate reliable and usable results. First the targets set by Philips Drachten are presented. Then the data that will be collected by the model is discussed.

4.7.1 Production targets of Philips Drachten

Philips Drachten has to produce at least 5.5 million products in the first year of production. A year consists of 48 production weeks and a week consists of 150 scheduled production hours. This means that on average $\frac{550000\,\frac{\#}{yr}}{48\frac{wk}{yr} * 150\frac{hr}{wk}} * 8\frac{hr}{shift} \approx 6111$ products should be produced each shift.

Philips Drachten has set a percentage of products that are expected to be produced compared to the maximum amount of products that could have been produced. This percentage has been set to 77%. With a processing time of 3 seconds per product (i.e. 12 seconds per carrier), this means that on average $\frac{8\frac{hr}{shift} * 3600\frac{s}{hr}}{3\frac{s}{\#}} * 77\% = 7392$ products are estimated to be produced each shift. This is of course well above the 6111 that should be produced.

When the cycle time is decreased to 2 seconds per product (i.e. 8 seconds per carrier), Philips Drachten hopes to produce 10 million products per year. This means that on average $\frac{10000000\,\frac{\#}{yr}}{48\frac{wk}{yr} * 150\frac{hr}{wk}} * 8\frac{hr}{shift} \approx 11111$ products should be produced each shift.

To summarize:

- The currently planned assembly line should have a minimum average production rate of 6111 products per shift.
- The average production rate is expected to be 7392 products per shift.
- After some improvements to the assembly line the minimum average production rate should be 11111 products per shift.

4.7.2 Data to be collected

A lot of output data could be collected by using the model. But not all this data is relevant for reaching the research objective. Data is collected on the throughput of the production line. This is collected by counting the number of products with acceptable quality (those products that do not fall off) that leaves the production line.

Philips Drachten works with a performance measure called Overall Equipment Efficiency (OEE). This performance measure gives the percentage of time that a production line is effectively producing. Production is lost due to three elements: breakdowns, blockage/starvation, and the fall off rate. These relate to process availability (PA), process performance (PP) and first pass yield (FPY) respectively. To calculate these values the following formulas are used:

$$PA = \frac{time\ the\ machine\ is\ not\ broken}{total\ production\ time}\ ,$$

$$PP = \frac{time\ the\ machine\ is\ actively\ working\ on\ a\ product}{time\ the\ machine\ is\ not\ broken}\ ,$$

$$FPY = \frac{products\ that\ pass\ test}{total\ products\ produced}\ .$$

OEE then follows from the following formula:

$$OEE = PA * PP * FPY$$

Since the cells all have the same cycle time, the cell which has the lowest OEE is considered to be the bottleneck in the assembly line and the assembly line will benefit the most if the performance of this cell is improved (compared to improving the performance of other cells).

The other relevant data to be collected would be the blockage and starvation of the overmolding machine in Cell 1. However, as explained in Subsection 4.5.4, the number of molding-carriers can be chosen in such a way that this never happens. Instead of measuring this blocking and starvation, the amount of products in the external buffer is collected. I have arbitrarily chosen to check this amount every 10 seconds (simulation time). The reason for collecting this data is that the size of the external buffer is limited and when this buffer is full, the molding machine will have to be shut down.

4.8 Conclusion

A discrete event simulator has been built. This simulator models the future assembly line at Philips Drachten. The simulator is built while using the following assumptions:

- Raw materials are always available
- There are always production orders to make new products
- The robot that handles products at the transition from molding-carriers to assembling-carriers and the external buffer is modelled as two separate machines
- Transport is not interrupted due to the physical dimensions of the carriers
- The size of the external buffer is not limited in the model

The parameters of the assembly line have been gathered and are integrated into the model. To the Time Till Failures a gamma distribution has been fitted. To the Time To Repair a lognormal distribution has been fitted. The processing times of the machines with unifeeders follow a discrete distribution.

The model has been validated by simulating a production line currently in use; experts of Philips Drachten and BWM have been consulted; results of the model have been discussed. All three show that the simulation model is a good representation of the future assembly line.

The model can now be used to generate data on the following performance measures: throughput of the assembly line, OEE and amount of products in the external buffer over time. These performance measures will be compared to targets set by Philips Drachten and to the performance that Philips Drachten expects.

The following research questions have been answered:

How can the assembly line be modelled?

What is the input data required for the model?

5 Scenarios and Results

The simulation will be run with different sets of system parameters. These sets will be presented in this chapter. Each set is immediately followed by the results of running the simulation model with these parameters. In Section 5.1 the influence of the number of carriers in the system is presented. In Section 5.2 the different allocations of available buffer space are simulated. In Section 5.3 the effects of expected improvements after the first year of production are considered. In Section 5.4 possible improvements are identified and simulated.

Unless stated otherwise, only changes to the system parameters presented in Section 4.5 are given. The number of runs per scenario (each with a different seed) is 100 for each scenario.

5.1 Number of carriers

The amount of carriers that should be placed in the system is one of the most important decision variables of this research. Both the amount of carriers that will results in the minimum required production and the amount that will give the maximum possible production are determined in this section.

5.1.1 Scenarios (number of carriers)

The number of carriers in the system will be varied. A combination is referred to as [c1, c2, c3], where c1, c2 and c3 represent the number of molding-carriers, assembling-carriers and printing-carriers, respectively. As stated in Subsection 4.5.4 the number of molding-carriers will not change. The number of assembling-carriers and printing-carriers will be varied. The minimum number of carriers is 1 and the maximum can be calculated by adding up all places in the buffers and machines that are in the carrier's loop. One carrier is subtracted to prevent a saturated carrier loop. So, for the assembling-carriers the number of carriers should be between 1 and 37 and for printing-carriers this should be between 1 and 70. Trying every possible combination of carriers would be cumbersome and unnecessary. Instead, trial runs are made to narrow down the combinations.

First, the number of printing-carriers is fixed on 16 carriers, which is a crude estimation of the number of carriers that will be necessary. This estimation is double the amount of carriers necessary if no breakdowns occur and all processing times are constant (see Subsection 4.5.4):

$$2 * \left\lceil \frac{1}{\max\left(P/T_{m \in loop}\right)} * \sum_{m \in loop} \left(P/T_m + T/T_m\right) \right\rceil .$$

The number of assembling-carriers is varied from 1 to 37. Only 1 simulation run is done per scenario. Data is collected on the amount of products produced. The results are displayed in Figure 6. Figure 6 b) shows the same graph as Figure 6 a) only zoomed in on the y-axis. This indicates that the necessary production is reached at 8 assembling-carriers and production no longer increases when more than 16 assembling-carriers are used. With 31 or more assembling-carriers the production decreases again. This indicates that the machines of the second carrier loop become increasingly blocked, due to the limited buffers.

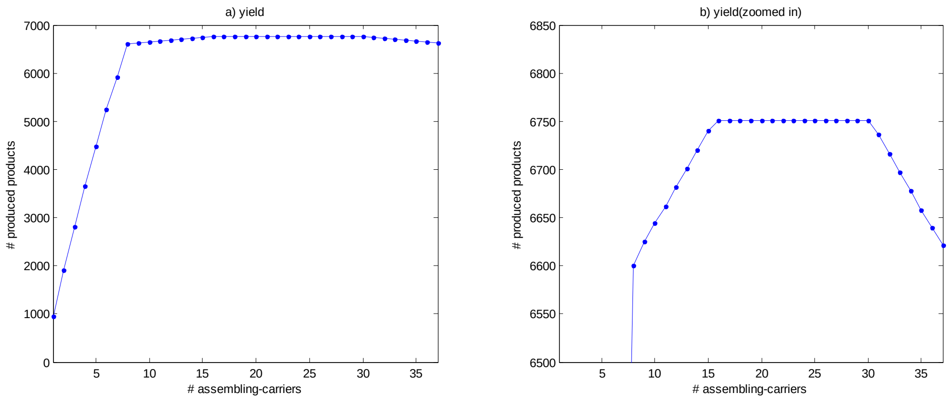


Figure 6. Products produced during one shift for a varying amount of assembling-carriers

Next, the number of assembling-carriers is fixed on 16 carriers, which is again double the amount of carriers necessary if no breakdowns occur and all processing times are constant. The number of printing-carriers is varied from 1 to 70. Only 1 simulation run is done per scenario. Data is collected on the amount of products produced. The results are displayed in Figure 7. This indicates that the necessary production is reached at 8 printing-carriers and production no longer increases when more than 27 printing-carriers are used. With 52 or more printing-carriers the production decreases. Again, this indicates increased blockage.

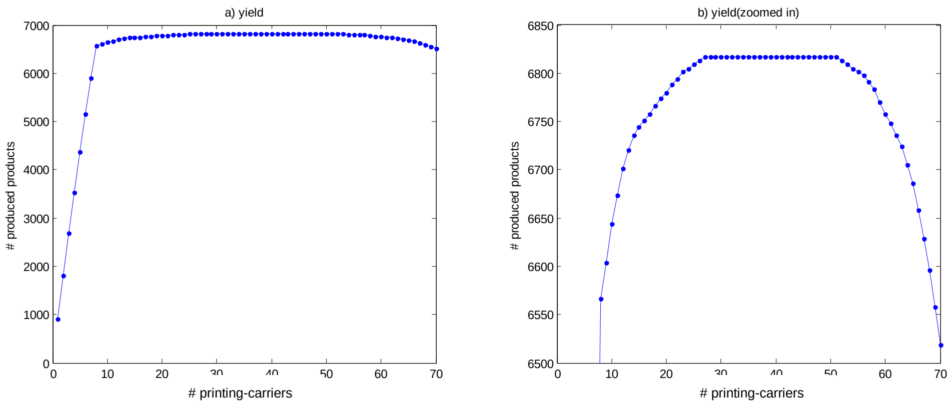


Figure 7. Products produced during one shift for a varying amount of printing-carriers

Both the region where just enough products are made (7 to 11 assembling-carriers and 7 to 11 printing-carriers) and the region where the production no longer increases (14 to 18 assembling-carriers and 25 to 29 printing-carriers) are simulated. The following 50 combination of carriers will be simulated:

	c1	c2	c3		c1	c2	c3		c1	c2	c3		c1	c2	c3		c1	c2	c3
1.	9	7	7	6.	9	8	7	11.	9	9	7	16.	9	10	7	21.	9	11	7
2.	9	7	8	7.	9	8	8	12.	9	9	8	17.	9	10	8	22.	9	11	8
3.	9	7	9	8.	9	8	9	13.	9	9	9	18.	9	10	9	23.	9	11	9
4.	9	7	10	9.	9	8	10	14.	9	9	10	19.	9	10	10	24.	9	11	10
5.	9	7	11	10.	9	8	11	15.	9	9	11	20.	9	10	11	25.	9	11	11

Table 3. Combination of carriers that are simulated in the region giving just enough production

26.	9	14	25	31.	9	15	25	36.	9	16	25	41.	9	17	25	46.	9	18	25
27.	9	14	26	32.	9	15	26	37.	9	16	26	42.	9	17	26	47.	9	18	26
28.	9	14	27	33.	9	15	27	38.	9	16	27	43.	9	17	27	48.	9	18	27
29.	9	14	28	34.	9	15	28	39.	9	16	28	44.	9	17	28	49.	9	18	28
30.	9	14	29	35.	9	15	29	40.	9	16	29	45.	9	17	29	50.	9	18	29

Table 4. Combination of carriers that are simulated in the region giving the maximum production

If these scenarios do not show the necessary results, then these scenarios will need to be expanded. For scenarios 1-25 this is done when the results do not show that using fewer carriers would mean that target average production of 6111 products per shift is not met. For scenario 26-50 this is done when the results do now show that adding one more carrier will increase the average production.

5.1.2 Results (minimum required number of carriers)

The simulation is run for scenarios 1-25 of Table 3. In Figure 8 the results are displayed. In Figure 8 c) the different scenarios are displayed; for each set of 5 scenarios the amount of printing-carriers increases by one per scenario; after 5 scenarios the amount of printing-carriers is reset again and one assembling-carrier is added.

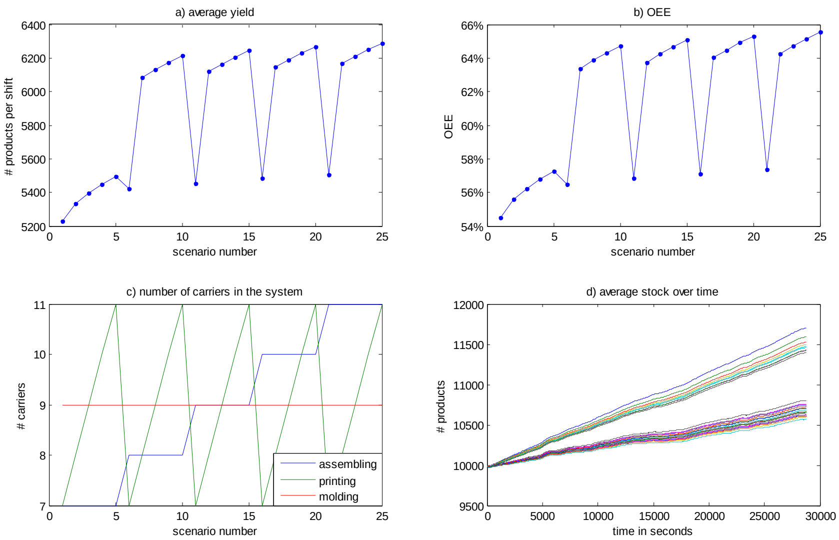


Figure 8. Results for different amounts of carriers in the system. a) the average yield for each scenario. b) the OEE for each scenario. c) the amount of carriers indicating the scenarios. d) the average stock in the external buffer over time for each scenario

In Figure 8 a) and b) the amount of produced products and the OEE are displayed. Adding more carriers clearly increases the throughput; after a set of 5 scenarios a sharp drop in production occurs due to removing 5 printing-carriers and only adding one assembling carrier. Figure 8 d) shows the average amount of products in the external buffer over time. As can be expected, a lower throughput of the assembly line results in a sharper increase of the amount of products in the external buffer.

The results show that the target production of 6111 is reached with a minimum of 26 total carriers, i.e. the combination of [9,8,9] or [9,9,8]. The amounts of products produced here have means of 6131 and 6119 products respectively, but with 95%-confidence intervals of [6041-6221] and [6028-6209], which have a lower bound under the target. The OEE only have values of 63.9% and 63.8% respectively. The products in the external buffer increase over time.

5.1.3 Results (amount of carriers for maximum throughput)

The simulation is run for the scenarios mentioned in scenarios 26-50 of Table 3. In Figure 9 the results are displayed. In Figure 9 c) the different scenarios are displayed; for each set of 5 scenarios the amount of printing-carriers increases by one per scenario; after 5 scenarios the amount of printing-carriers is reset again and one assembling-carrier is added.

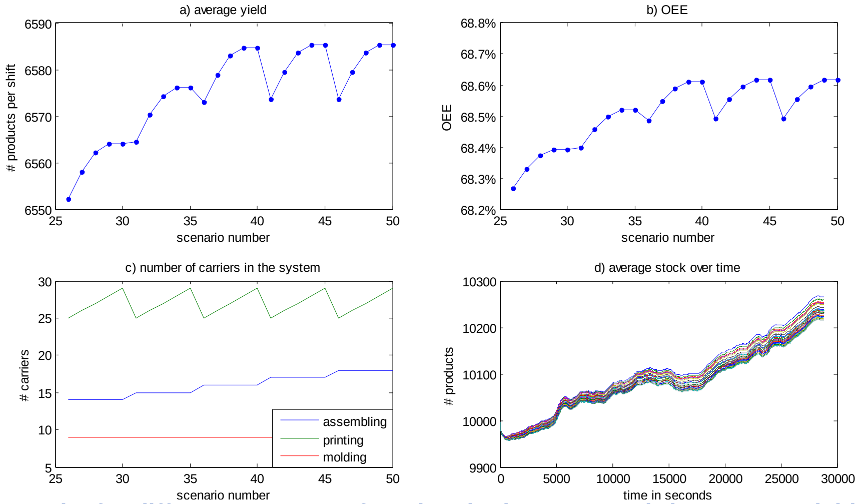


Figure 9. Results for different amounts of carriers in the system. a) the average yield for each scenario. b) the OEE for each scenario. c) the amount of carriers indicating the scenarios. d) the average stock over time for each scenario

In Figure 9 a) and b) the amount of produced products and the OEE are displayed. After a set of 5 scenarios a sharp drop in production happens due to removing 5 printing-carriers and only adding one assembling carrier. Figure 9 d) shows the average amount of products in the external buffer over time. The results show that production is no longer increased by adding more than 16 assembling-carriers or more than 28 printing-carriers. These statements have been tested using a paired-t test, see Appendix B. The average production is 6585 products with a 95%-confidence interval of [6500-6670]. OEE is 68.6%. The amount of products in the external buffer slightly increases over time.

5.2 Buffer allocation

Next to the amount of carriers, the allocation of available buffer space is also a very important variable of this research.

5.2.1 Scenarios (buffer allocation)

The distance in between the cells can vary as explained in Subsection 4.5.3. This distance directly relates to the amount of carriers that the buffers in between the cells can hold. The buffer sizes that can change because of this are those at Machines 6, 11, 13, 14 and 17. Because the cells are connected through a carrier loop, the buffer sizes of Machines 6 and 11 are dependent. The same holds for the available space at Machine 13 compared to that at Machines 14 and 17. There is a minimum buffer size due to work floor regulations at Philips Drachten. There is a maximum buffer size due to a maximum length that the line can have. The different cases that are simulated are displayed in Table 5.

Each of the configurations are simulated with these three carrier combinations: [9,16,28], [9,17,28] and [9,16,29]. These are the combination determined in Section 5.1 which results in maximum production and this combination plus 1 assembling-carrier or printing-carrier. Afterwards, each of the buffer configurations is simulated with these two carrier configurations: [9,9,8] and [9,8,9].

This means that each of the cases in Table 5 is simulated for 5 carrier configurations, resulting in $15 * 5 = 45$ scenarios.

	Buffer Machine 6	Buffer Machine 11	Buffer Machine 13	Buffer Machine 14	Buffer Machine 17
	between 3rd and 2nd Cell	between 2nd and 3rd Cell	between 5th and 3rd Cell	between 3rd and 4th Cell	between 4th and 5th Cell
1.	22 places	10 places	43 places	6 places	6 places
2.	21 places	9 places	44 places	7 places	6 places
3.	21 places	9 places	44 places	6 places	7 places
4.	20 places	8 places	45 places	8 places	6 places
5.	20 places	8 places	45 places	7 places	7 places
6.	20 places	8 places	45 places	6 places	8 places
7.	19 places	7 places	46 places	9 places	6 places
8.	19 places	7 places	46 places	8 places	7 places
9.	19 places	7 places	46 places	7 places	8 places
10.	19 places	7 places	46 places	6 places	9 places
11.	18 places	6 places	47 places	10 places	6 places
12.	18 places	6 places	47 places	9 places	7 places
13.	18 places	6 places	47 places	8 places	8 places
14.	18 places	6 places	47 places	7 places	9 places
15.	18 places	6 places	47 places	6 places	10 places

Table 5. Buffer sizes that are simulated

5.2.2 Results (buffer allocation)

The resulting throughputs for running the scenarios with the first three carrier configurations are displayed in Figure 10. The throughput for the scenarios with [9,16,28] carriers (the blue line which cannot be seen in the figure) seems to always be the minimum result of the scenario with the two other carrier configurations. As can be expected, the results show that, with a buffer allocation that is more shifted towards the assembling-carrier loop (scenarios 1-6), adding an extra assembling-carrier will increase the throughput, but adding a printing-carrier will not. With a buffer allocation that is more shifted towards the printing-carrier loop (scenarios 7-15) the opposite holds true: adding an extra printing-carrier will increase the throughput, but adding an assembling-carrier will not.

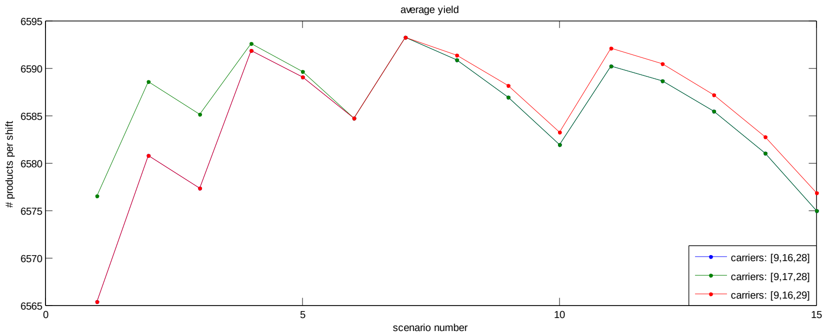


Figure 10. Production results for different buffer allocations

The optimum is reached at scenario 7 with 7 places for buffering carriers between the Assembly Cell and the Welding Cell, 9 places between the Welding Cell and the Printing Cell and 6 places between the Printing Cell and the Packaging Cell. With this allocation the production line can produce on average 6593 products per shift with a 95%-confidence interval of [6509-6677].

The results for running the scenarios with the carrier configurations which will give the required minimum production are displayed in Figure 11. This shows that buffer allocation has no impact on the throughput when such a small number of carriers is used inside the loops. This indicates that the buffers at these machines never are full, which indicates that the machines in front are never blocked.

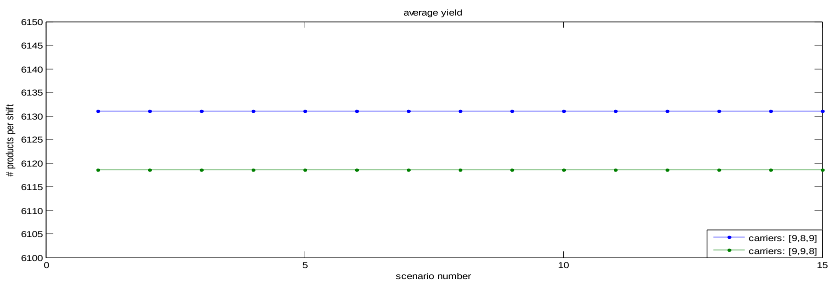


Figure 11. Results for different buffer allocations with the minimumrequired production

5.3 Expected future improvements of the assembly line

Philips Drachten expects that after one year of production most inefficiencies have been dealt with and that the production line will run smoother. Also, the demand for the product might have increased a lot and the assembly line will then have to be improved.

The parameters of the optimal scenario from Section 5.2 are used for these simulations: buffer space in front of Machines 6,11,13,14,17 is configured to 19,7,46,9,6 places respectively; a carrier combination of [9,16,28] is used.

5.3.1 Scenarios (future improvements)

In the first year a Fall Off Rate (FOR) of 22% is expected for the products coming from the overmolding machine. This is expected to be improved to only 5% in the following years. The cycle time (processing time per product) of the machines in the Molding Cell can then be changed from 2.5 seconds to 3 seconds to synchronize it with the rest of the assembly line. Increasing cycle time can seem like an undesired decision to make. The argument for this is that if the cycle time of 2.5 seconds is maintained, then the rest of the assembly line cannot keep up and this will inevitably result in more blockage of the overmolding machine.

The end consumer demand of the product might increase substantially. This means more products will have to be produced. With the current production line this is not possible, but with additional investments the cycle time of the entire production line can be brought down to 2 seconds. Minor changes to the lay-out of the assembly line will have to be made. But since the changes are small, simulating the assembly line with faster processing times will give a good estimation of the output of this improved line. The three scenarios that are simulated are shown in Table 6. The first scenario here is the same scenarios from the previous two sections.

	FOR molding	PT Machines 1-4	PT Machines 7, 9, 14-17	PT Machine 12	PT Machines 8 & 10*
1.	22%	10 s	12 s	3 s	12 s
2.	5%	12 s	12 s	3 s	12 s
3.	5%	8 s	8 s	2 s	8 s

** mean values of variable processing times*

Table 6. Processing times that are simulated

5.3.2 Results (future improvements)

The scenario with 2.5 seconds cycle time and 22% FOR for the Molding Cell and the second scenario with 3 seconds cycle time and 5% FOR for the Molding Cell give exactly the same production results. This is due to the decoupling by the external buffer. What is more interesting is how the amount of products in the external buffer behaves over time; this is shown in Figure 12. On average, the overmolding machine in the second scenario is producing more products than the machine in the first scenario. This means the external buffer will be filled quicker and the overmolding machine will have to be stopped, because it can no longer release its products.

The third scenario, where the cycle time of the entire assembly line in brought down to 2 seconds has a throughput of 9693 with a 95%-confidence interval of [9563-9823]. The OEE is 67.3%. This is well below the 11111 products that Philips Drachten expects. In order to reach this production of 11111 products per shift additional improvements will have to be made to the assembly line. Some improvements are discussed in the following section.

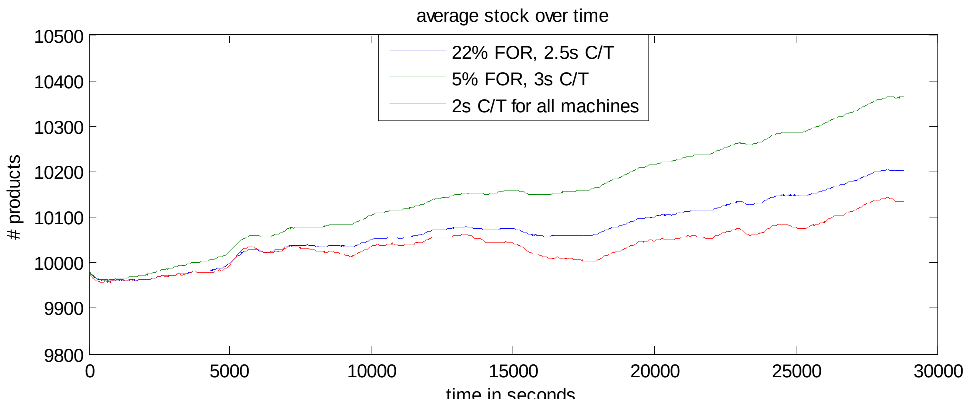


Figure 12. Amount of products in the external buffer over time for three different scenarios

5.4 Other scenarios

Based on the results in the previous sections, possible improvements are identified and simulated. First the bottleneck of the assembly line is identified and improved. After that the theoretical improvements of failure times and repair times are considered.

5.4.1 Scenarios (bottleneck improvement)

The throughput of the assembly line is limited by the bottleneck in the line. By focussing on improvements of this bottleneck, the performance of the entire assembly line should improve. It is beneficial to already consider this while the processes are designed (Hinckeldeyn et al., 2014). As stated in Subsection 4.7.2 the cell which has the lowest Overall Equipment Efficiency (OEE) is considered to be the bottleneck of the entire assembly line. Unfortunately the Fall Off Rate is not specified for each individual production cell. To this end the OEE is adapted to just incorporate the Process Availability (PA) and the Process Performance (PP). This new performance indicator is called the Cell Efficiency (CE):

$$CE = PA * PP$$

The CE is calculated by using the simulation results for the first year with the optimal amount of carriers and buffer allocation (the first scenario from Section 5.3). PA is around 90% for all machines (because it is mostly determined by the MTTF and MTTR values. This means that PP is the determining factor here.

Cell:	Molding	Assembling	Welding	Printing	Packaging
Cell Efficiency:	81%	73%	66%	72%	72%

This shows that the Welding Cell is the bottleneck. This cell only has one element, the welding carousel. By slightly decreasing the processing time of the carousel, the performance of the assembly line should improve. This has been discussed by the process engineers responsible for the welding. They stated that this processing time can be decreased without adding or expanding equipment; only the process control parameters need to be adjusted. This will result in no extra operational cost of the welding carousel. The only costs are the time that the process engineer spends on fine-tuning the carousel (which needs to be done anyway for the normal processing time of 3 seconds). Table 7 shows the processing times which are simulated.

	PT Machine 12		PT Machine 12		PT Machine 12		PT Machine 12
1.	3 s	2.	2.875 s	3.	2.75 s	4.	2.625 s
5.	2.5 s	6.	2.375 s	7.	2.25 s		

Table 7. Processing times of the welding carousel that are simulated

5.4.2 Results (bottleneck improvement)

The results for varying processing time of the welding carousel are presented in Figure 13. In Figure 13 c) the processing times of the welding carousel for each scenario is shown. As can be seen in Figure 13 a) and b), by decreasing this processing time, the throughput and efficiency of the assembly line increase. When the processing time is decreased to 2.25 seconds the improvement compared to 3 seconds is 88 products more per shift with a 95%-confidence interval of [77-98]. This improvement is very small, but still welcome as it is free.

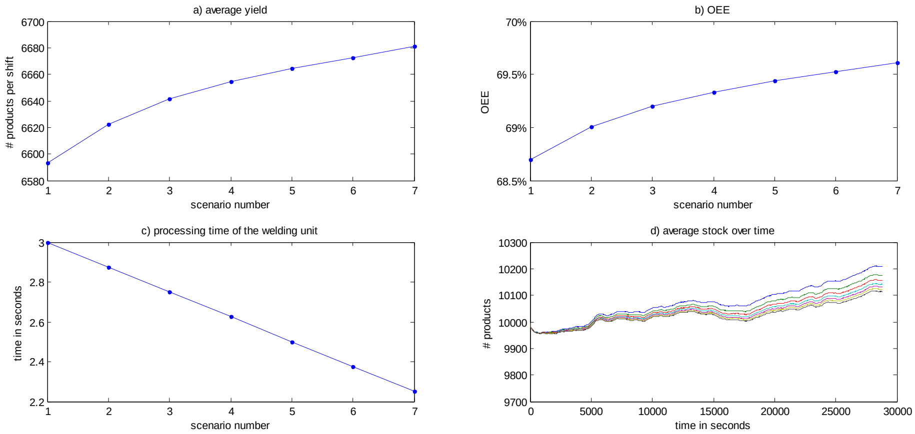


Figure 13. Results for different processing times of the welding unit. a) the average yield for each scenario. b) the OEE for each scenario. c) the processing time of the welding unit indicating the scenarios. d) the average stock over time for each scenario

5.4.3 Scenarios (cell availability)

Another possible improvement relates to the production capacity that is lost due to breakdowns. Breakdowns do not only affect the cell at which the breakdown occurs, but they also indirectly affect the other cells in the production line. By increasing the MTTF of the last four production cells, or by decreasing the MTTR, I expect the average throughput will increase. Values for the MTTF and MTTR in Table 8 are simulated. The probability distributions for time to failure and time to repair are still given by:

$$TTF \sim \text{Gamma}(\ 0.365\ ,\ MTTF/0.365\ )$$

$$TTR \sim \text{Lognormal}(\ \ln(MTTR) - \tfrac{1}{2} \cdot 1.0641^2\ ,\ 1.0641\ )$$

These simulations are done for:

- the assembly line with a cycle time of 3 seconds (and 5% FOR after molding)
- the assembly line with a cycle time of 2 seconds (and 5% FOR after molding)

How exactly these values can be improved are not discussed in this thesis and is considered a subject of further research for Philips Drachten. Possible options are to research preventive maintenance (Das et al., 2007)

	MTTF Cells 2-5	MTTR Cells 2-5		MTTF Cells 2-5	MTTR Cells 2-5		MTTF Cells 2-5	MTTR Cells 2-5
1.	1350 s	150 s	7.	1350 s	120 s	13.	1350 s	90 s
2.	1800 s	150 s	8.	1800 s	120 s	14.	1800 s	90s
3.	2250 s	150 s	9.	2250 s	120 s	15.	2250 s	90 s
4.	2700 s	150 s	10.	2700 s	120 s	16.	2700 s	90 s
5.	3150 s	150 s	11.	3150 s	120 s	17.	3150 s	90 s
6.	3600 s	150 s	12.	3600 s	120 s	18.	3600 s	90 s

Table 8. MTTF and MTTR values that are simulated

5.4.4 Results (cell availability)

The results for the assembly line with 3 seconds cycle time are displayed in Figure 14. In Figure 14 c) the cell availability is displayed, this is the percentage of time that the cell is not broken and is calculated by the following formula: $\frac{MTTF}{MTTF+MTTR}$. For each set of 6 scenarios the MTTF increases by 450 seconds for each scenario. After 6 scenarios the MTTF is reset and the MTTR decreases by 30 seconds. The production per shift and the OEE are displayed in Figure 14 a) and b). This shows that for these changes in MTTF and MTTR, huge improvements are made in the performance indicators.

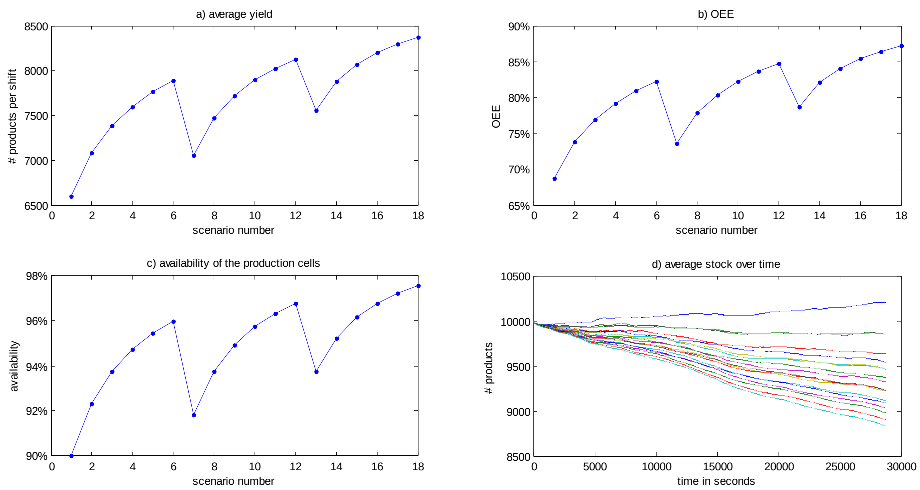


Figure 14. Results for different MTTF and MTTR values with an assembly line with 3 seconds cycle time. a) the average yield for each scenario. b) the OEE for each scenario. c) availability of the production cells. d) the average stock over time for each scenario

In Figure 15 the results for the assembly line with 2 seconds cycle time are presented. This shows relatively the same improvements as for the scenarios with 3 seconds cycle time.

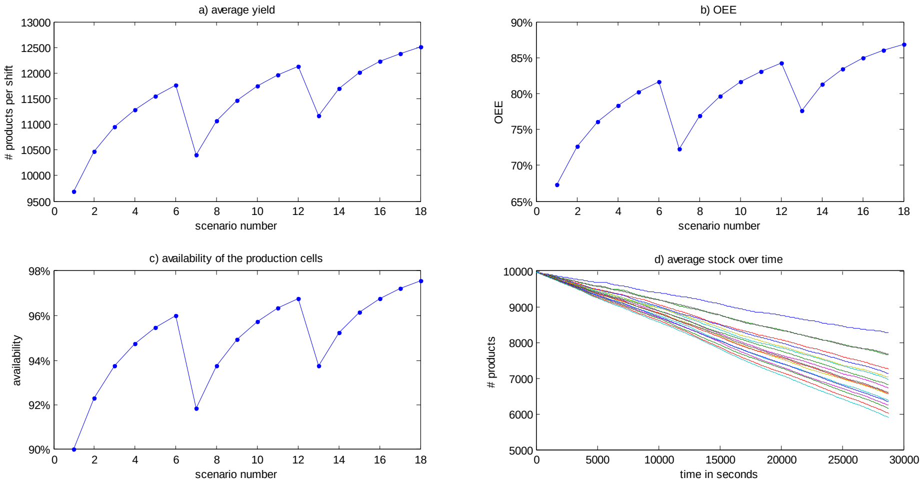


Figure 15. Results for different MTTF and MTTR values with an assembly line with 2 seconds cycle time. a) the average yield for each scenario. b) the OEE for each scenario. c) availability of the production cells. d) the average stock over time for each scenario

Because only the last four production cells are improved and the first cell is not, the average stock in the external buffer decreases. This means that eventually the external buffer will be completely empty and the production is completely determined by the output of the Molding Cell. This should be taken into account when improving MTTF and MTTR values.

5.5 External buffer

To gain insight in how much the external buffer will be used, the stock over time in the external buffer is examined. This is done for the results from all 100 runs of the scenarios from Section 5.3 (Table 6), the maximum stock level and the minimum stock level of the number of products in the external buffer is determined. Then the amount of runs which stayed within a certain limit from the initial stock in the external buffer are summed up. For increments of 500 products the results are shown in Table 9 and Table 10.

	≤0	≤500	≤1000	≤1500	≤2000	≤2500	≤3000
2015	3	50	78	94	99	100	100
2016	2	42	75	92	99	100	100
2016 improved	4	45	71	83	92	99	99

Table 9. Summation intervals for maximum stock levels

	≥0	≥-500	≥-1000	≥-1500	≥-2000	≥-2500	≥-3000
2015	0	65	88	96	100	100	100
2016	0	73	90	98	100	100	100
2016 improved	0	49	74	85	93	98	100

Table 10. Summation intervals for minimum stock levels

To be clear: Table 9 shows the amount of runs that did not surpass the limits at the top of the table. For instance, for the scenario of 2015 the amount of runs where the stock level of the external buffer did not grow more than 1000 products is 78 times out of the total of 100 runs. This implies that 100-78=22 runs did surpass this limit of 1000.

The same goes for Table 10, only here the values are displayed for the amount of runs where the stock level of the external buffer did not drop more than the limits at the top of the table. For instance, for the improved scenario of 2016, the amount of runs where the stock level of the external buffer did not shrink more than 1500 products is 85 out of the total of 100 runs.

In the real production line the external buffer will not be so large. With a more realistic size, it can happen that the external buffer becomes completely empty. When this occurs, newly arriving (empty) assembling-carriers can no longer be loaded with products, resulting is loss of equipment efficiency. On the other hand it can happen that the external buffer is filled completely. When this occurs, newly arriving (full) molding-carriers can no longer be unloaded when there is no assembly-carrier available, resulting in the highly unwanted blockage or starvation of the overmolding machine.

For the first year and the second year with 3 seconds cycle time the stock in the external buffer only falls outside the interval of $stock_{t=0} \pm 2000$ once. This means that when an initial stock of 2000 is used for a buffer which can hold a total of 4000 products, the probability is very low that stock outs or overflows of the buffer occur.

When the cycle time of the machinery is improved to 2 seconds, the amount of products in the external buffer shows the same behaviour only with increased effect. For 97% of these runs, the stock never falls outside the interval of $stock_{t=0} \pm 2500$. Only once the $stock_{t=0} + 2500$ is exceeded.

From the results displayed in Figure 12 it was concluded that the average stock is increasing over time. This means that (on average) the external buffer is slowly filled and there will regularly be occurrences of a full external buffer. To keep control of the quality of products, the overmolding machine can be shut down. It can be restarted again when the amount of products in the external buffer has dropped below a certain threshold value. There is a 15 minute start-up time for the overmolding machine before it will produce products again.

5.6 Conclusion

The following factors have been simulated:

- 25 carrier configurations around the target production rate
- 25 carrier configurations around the maximum production rate
- 15 different buffer allocations
- System parameters of the first year and of the second year
- 7 speeds of the welding carousel (Machine 12)
- Combinations of 6 different MTTF values with 3 different MTTR values

The results showed that in order to reach the target average throughput of 6111 products per shift, [9,8,9] or [9,9,8] carriers should be placed in the carrier loops, giving 95%-confidence intervals of the average production of [6041-6221] and [6028-6221] products per shift respectively. To maximize the throughput at least 9 molding-carriers, 16 assembling-carriers and 28 printing-carriers are needed, giving a 95%-confidence interval of average [6500-6670] products produced per shift.

Using more than 30 assembling-carriers or more than 51 printing-carriers will be counterproductive for the amount of products produced.

The system performs best with this allocation of buffer spaces between the production cells: Molding<8>Assembly<7>Welding<9>Printing<6>Packaging. This increases the confidence interval of the average production to [6509-6677] products per shift.

If the FOR after molding improves, then increasing the cycle time of the machines in the Molding Cell to 3 seconds has no impact on the throughput of the assembly line. But not doing so could cause the external buffer to be filled completely much faster.

Increasing just the processing time of the welding carousel has a positive impact on the throughput of the assembly line. The increase in production has a 95%-confidence interval of [77-98] products per shift.

Improving MTTF and MTTR of the last 4 production cells greatly improves the throughput, with possible improvements of over 15%.

The amount of products that is stored in the external buffer can vary a lot. From the initial stock the amount of products in the stock will slowly increase over time. During eight hours the stock will rarely have increased or decreased by more than 2000 products.

6 Conclusion & Recommendations

In this chapter the main research question is answered (Section 6.1) and recommendations are given to Philips Drachten (Section 6.2).

6.1 Conclusion

The main research question of this research is:

> *What is the effect of the number of carriers and the allocation of buffer places within the assembly line on the throughput of the assembly line and on the starvation/blockage of the overmolding machine?*

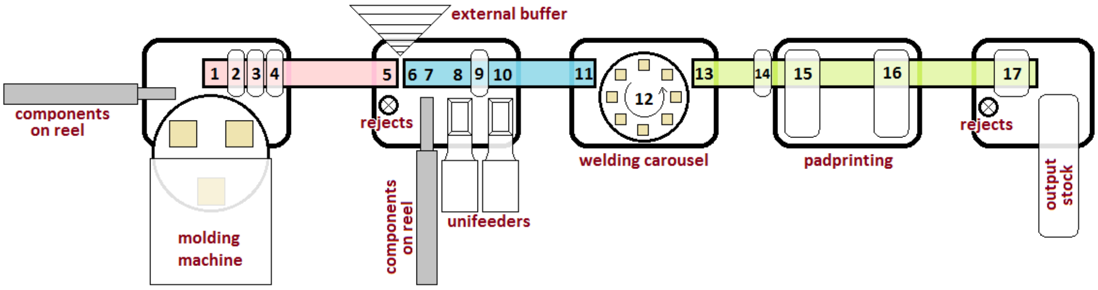
By answering sub-questions an answer can now be given to this question.

6.1.1 Summary of answering the research sub-questions

The sub-questions that have been answered are:

What will the assembly line look like?
What literature is available that can help with the problem?
How can the assembly line be modelled?
What is the input data required for the model?
What design of the assembly line is best for Philips Drachten?

In the first sub-question the assembly line has been described, resulting in the schematic overview of Figure 2. There are 17 machines divided over 5 production cells and 3 carrier loops.



Copy of Figure 2. Schematic overview of the assembly line

Next, the literature has been consulted. This showed that the system can be considered as: a single class multi-loop closed manufacturing system with unreliable machines and finite buffers.

Different techniques for modelling the assembly line were considered. The network showed too complex to be analyzed analytically due to processing times, failure times and repair times not having the memoryless property and the buffers in the system being finite. Of the remaining options, discrete event simulation showed the most promising and was chosen.

The assembly line was modelled using Matlab. The system parameters were estimated by consulting experts and studying similar production lines. The model was validated by consulting experts and by comparing simulation results of an adapted model to a production line which is currently in use.

Different scenarios were simulated to explore various options in designing the production line. The results were analyzed. The recommendations made in Section 6.2 are based on this analysis.

6.1.2 Answer to the main research question

What is the effect of the number of carriers and the allocation of buffer places within the assembly line on the throughput of the assembly line and on the starvation/blockage of the overmolding machine?

The amount of carriers in the system has a substantial effect on the throughput of the assembly line. Target production of 6111 products per shift can be met by using 9 molding-carriers, 9 assembling-carriers and 8 printing-carriers.

From 9 to 16 assembling-carriers the production will increase if more carriers are used. Putting 17 to 30 assembling-carriers in the system has no effect on throughput. 31 or more assembling-carriers decrease throughput due to blockage.

From 9 to 28 printing-carriers the production will increase if more carriers are used. Putting 28 to 51 printing-carriers in the system has no effect on throughput. Using 52 or more printing-carriers will cause too much blockage in the assembly line and throughput will decrease.

The allocation of buffer space has limited effect on the throughput. The buffer space between the Welding Cell and the Pad printing Cell benefits more from a bigger size than the buffer space between the Pad printing Cell and the Welding Cell. The best allocation of the buffer space before and after the Welding Cell has been determined to be 7 and 9 respectively.

As long as 9 molding-carriers are used, there is no starvation/blockage of the overmolding machine. No matter the remaining number of carriers and the allocation of buffer spaces

6.2 Recommendations

Recommendations are now given on the amount of carriers that should be used in the system, the allocation of buffer space, the size and use of the external buffer and focus of improvements.

This is followed by future research that can be done based on the research of this thesis.

6.2.1 Number of carriers

Throughput and OEE are very important performance measures. By maximizing the throughput, the demand can be fulfilled quicker and production can be scheduled in less time. However, machine operators will still need to be paid even when the assembly line is not working. So increasing production when this is not necessary is not that beneficial. For this reason I recommend using 9 molding-carriers, 9 assembling-carriers and 8 printing-carriers. This will results in the necessary production 5.5 million products per year with the minimal amount of carriers.

When demand for the products increases, more carriers can be bought and put into the system. By adding 7 more assembling-carriers (16 total) and 20 more printing-carriers (28 total) production can be increased by over 400 thousand products per year. With one carrier costing €500, this means an additional investment of €13500. When demand increases even more, then additional machinery will have to be purchased.

6.2.2 Allocation of buffer space

There exists an optimal allocation of buffer space that maximizes throughput. There is no reason not to design the system with the optimal allocation. To obtain the optimal allocation, the Molding Cell, Assembly Cell and Packaging Cell remain on their currently planned positions, The Welding Cell is moved about 12.5 centimetres towards the Assembly Cell and the Pad printing Cell is moved about 25 centimetres towards the Packaging Cell.

6.2.3 External buffer

I recommend an external buffer that can contain 4000 products. An initial stock of 2000 should try to be maintained.

With an initial stock of 2000 products the probability of the external buffer running empty are very low. With the possibility of adding another 2000 products to this initial amount, the probability that the overmolding machine has to stop is very low for one shift.

However, on average the stock in the external buffer increases over time. This has to either be taken into account with the production scheduling, or during the shift. When during a shift the external buffer is filled completely, the overmolding machine can be switched off. It can be started again if the stock drops below a certain threshold level. I recommend using a threshold level of 2300 products. This takes into account the 15 minute start-up period for the overmolding machine. During these 15 minutes at most $\frac{15min * 60\frac{s}{min}}{3\frac{s}{\#}} = 300\#$ products are taken out of the stock; with a threshold of 2300 products this means the stock returns to the initial level of 2000 products.

If the cycle times are improved to 2 seconds, then I recommend a buffer that can hold 5000 products and an initial stock of 2500 products. The threshold value of when the overmolding machine is turned on again should then be 2950 products.

6.2.4 Additional improvements

By decreasing the processing time of the welding carousel, the throughput of the assembly line is improved. This can be done for minimal costs.

The biggest loss of OEE is caused by machine breakdowns. It is worth to research if and how either MTTF can be increased or MTTR can be decreased. Both will greatly improve OEE and the throughput of the assembly line.

6.2.5 Future research

Once the assembly line is built and is producing, the performance of the assembly line can be studied. Real values of estimated parameters can be found and possible other improvements to the simulation model might be made.

The simulation model can be used for other production lines at Philips Drachten. Improvements on the amount of carriers in a system or on the processing times of machines with adjustable machines can be found.

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Appendix A - Model factors

This appendix deals with additional factors of the simulation model. First the seeds of the random number streams are presented. This is followed by a statement about carrier numbers.

Number of runs

To determine the necessary number of runs, the formula from Subsection 3.3.3 is used:

$$t_{n-1,1-\alpha/2} * \frac{1}{\sqrt{n}} * \frac{s_{X_n}}{|\bar{X}_n|} \leq \frac{\gamma}{1+\gamma}$$

As an example the results from the best scenario of Section 5.1 is used (scenario 39). The first n for which the formula holds is n=12. This means that 12 is the minimum amount of runs necessary to get reliable results. This is displayed in Figure 16, where the blue line is the relative error of the results and the red line is the maximum allowed relative error.

The mean and standard deviation when using n=12 runs are 6657 and 480.62 respectively, giving: 0.0459 ≤ 0.4760, or a relative error of 5%.

When n=100 runs are used the man and standard deviation are 6585 and 508.88 respectively, giving: 0.0153 ≤ 0.4760, or a relative error of 1.5%.

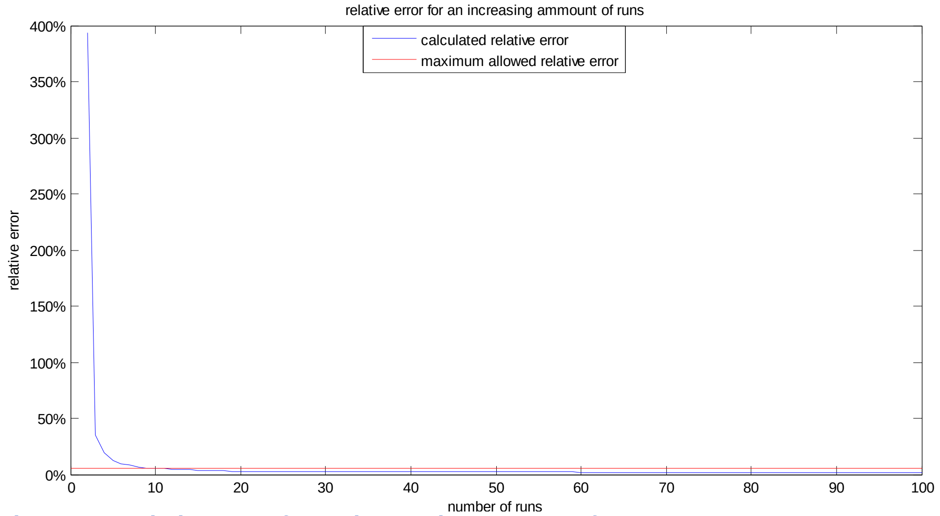

Figure 16. Relative error for an increasing amount of runs

Random number seeds

The random number streams that used to model randomness are the Matlab implementation of the 19937-Mersenne Twister. These streams require a seed. The seed numbers are displayed in Table 11 where rc is the runcounter of the scenario. This seeding makes sure the same pseudo random numbers are used for each scenario, but the numbers are still statistically independent between runs within a certain scenario.

stream	seed
Cell1 failure	1100 +rc-1
Cell2 failure	1200 +rc-1
Cel3 failure	1300 +rc-1
Cell4 failure	1400 +rc-1
Cell5 failure	1500 +rc-1

stream	seed
Cell1 repair	2100 +rc-1
Cell2 repair	2200 +rc-1
Cel3 repair	2300 +rc-1
Cell4 repair	2400 +rc-1
Cell5 repair	2500 +rc-1

stream	seed
FOR molding	3100 +rc-1
FOR Assembly	3200 +rc-1

stream	seed
PT Machine 6	4100 +rc-1
PT Machine 8	4200 +rc-1

Table 11. Seed numbers for random number streams

Carrier numbers

With the way I programmed the assembly line, there is a distinction between carriers; each carrier is given a number and can be tracked individually through the system. This distinction is not strictly necessary since all carriers of one type are exactly the same and are always in the same order. However, the distinction made debugging much easier.

Appendix B - Paired t-test

Since the same pseudo random numbers are used for each scenario, the scenarios can be compared using a paired-t test.

This test uses the distribution of the difference of two sample distribution and checks weather the mean of these distributions can be considered to differ. When the means differ, a confidence interval can be calculated indicating by how much the means differ.

The test statistic of this test is calculated as follows:

$$D = X_1 - X_2$$

$$t = \frac{\overline{D}}{s_D * \sqrt{n}}$$

Where X_1 and X_2 are the two sample distributions. D is the distribution of the difference. t is the test statistic. $\overline{D}$ is the mean of D and s_D is the sample standard deviation of D. n is the size of the samples.

When t>0.05, the likelihood of distribution X_1 having a higher mean than distribution X_2 is very large. When t<-0.05 the likelihood of distribution X_1 having a lower mean than distribution X_2 is very large. When -0.05<t<0.05 the possibility that X_1 and X_2 have the same mean cannot be dismissed.

When two distributions are considered to be different, a confidence interval of the difference can be constructed. The lower and upper limits of the interval are given by:

$$[\overline{D} \pm \frac{t_{n-1,1-\alpha} * s_D}{\sqrt{n}}]$$

Where $t_{n-1,1-\alpha}$ is the critical value of the student-t distribution with n-1 degrees of freedom and a significance of 1-α.

In this research n is always equal to 100 and α is chosen to be 5%. This corresponds to a critical value of 1.6604, effectively setting the lower and upper limits of the interval to:

$$[\overline{D} \pm 0.16604 * s_D]$$

Appendix C - Event flow charts

As explained in Subsection 4.4.4, events are handled in the order they occur. During the handling of each event, new events can be added to the event manager lists. Once the handling is complete, the event is deleted from the list and the next event about to happen will be handled. In this appendix I elaborate on the way the simulation model handles events.

In the following flowcharts all events that are incorporated in the model are displayed. The flow charts all have the same structure. An event starts at a green ellipse. The model then follows the flowchart until a red ellipse. At this point the event has been processed and can be deleted from the event list. Blue blocks are actions: either the system state variables are changed or new events are planned. Orange blocks direct flow: the system state or the input parameters of the event are checked and the flow is continued based on this check. Purple blocks are data gathering actions: information is gathered on performance measures. Dark blue blocks contain a lot of other flow steps and are summarized to increase readability.

Cell events are handled in the manner displayed in Figure 17. The input parameters of these events are: runtime, cell number and event type.

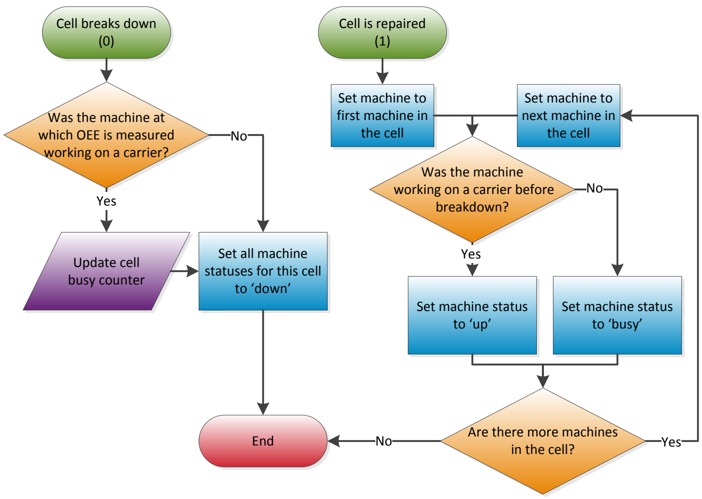

Figure 17. Flow diagram for handling events at Cells

Machine Events are handled in the manner displayed in Figure 18. The input parameters of these events are: runtime, machine number, carrier number and event type.

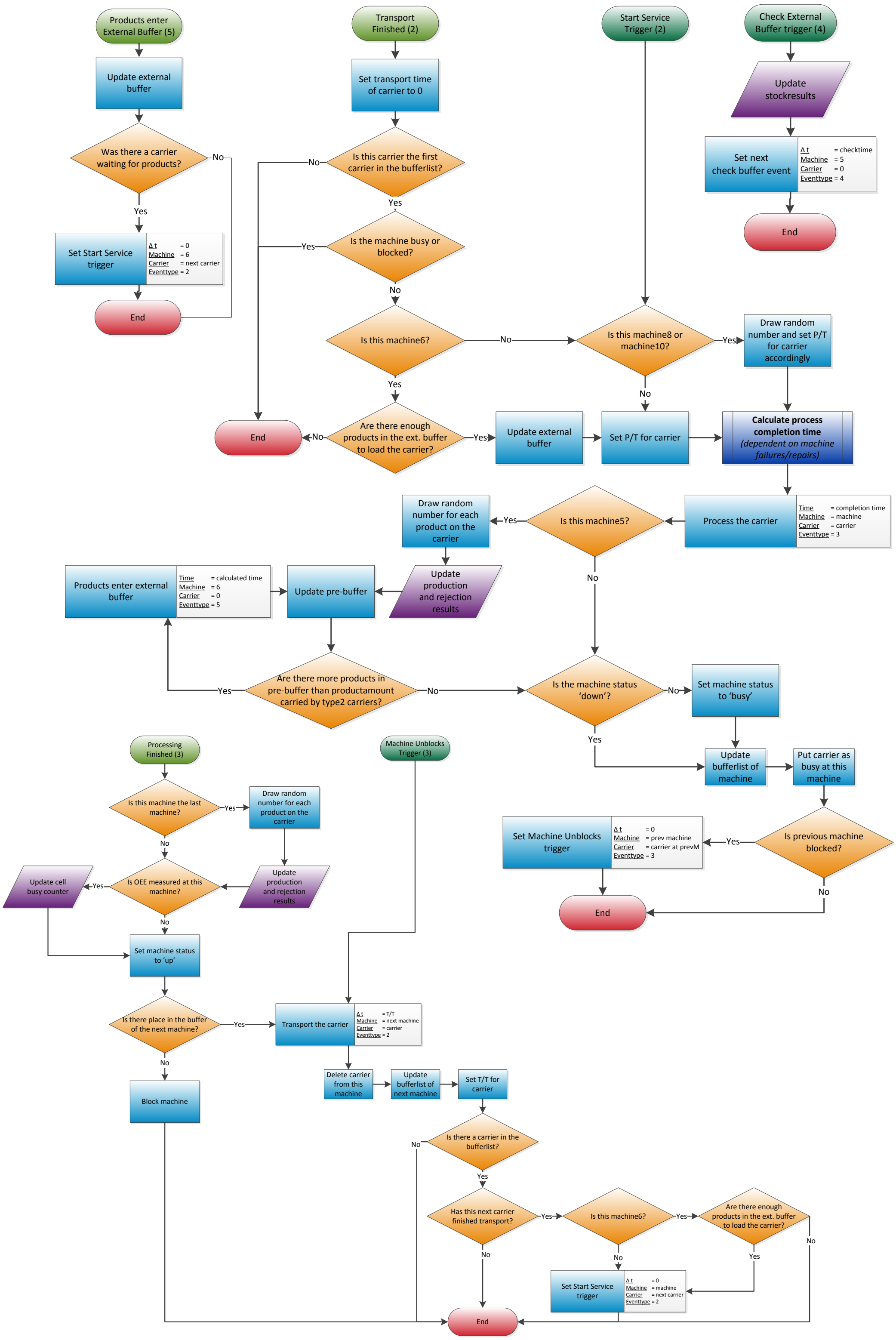

Figure 18. Flow diagram for handling events at standard Machines

Welding events are handled in the manner displayed in Figure 19. For Machines 11 and 13 the input parameters of these events are: runtime, machine number, carrier number and event type. For Machine 12, the welding carousel, the input parameters of these events are: runtime, carousel turning steps and event type.

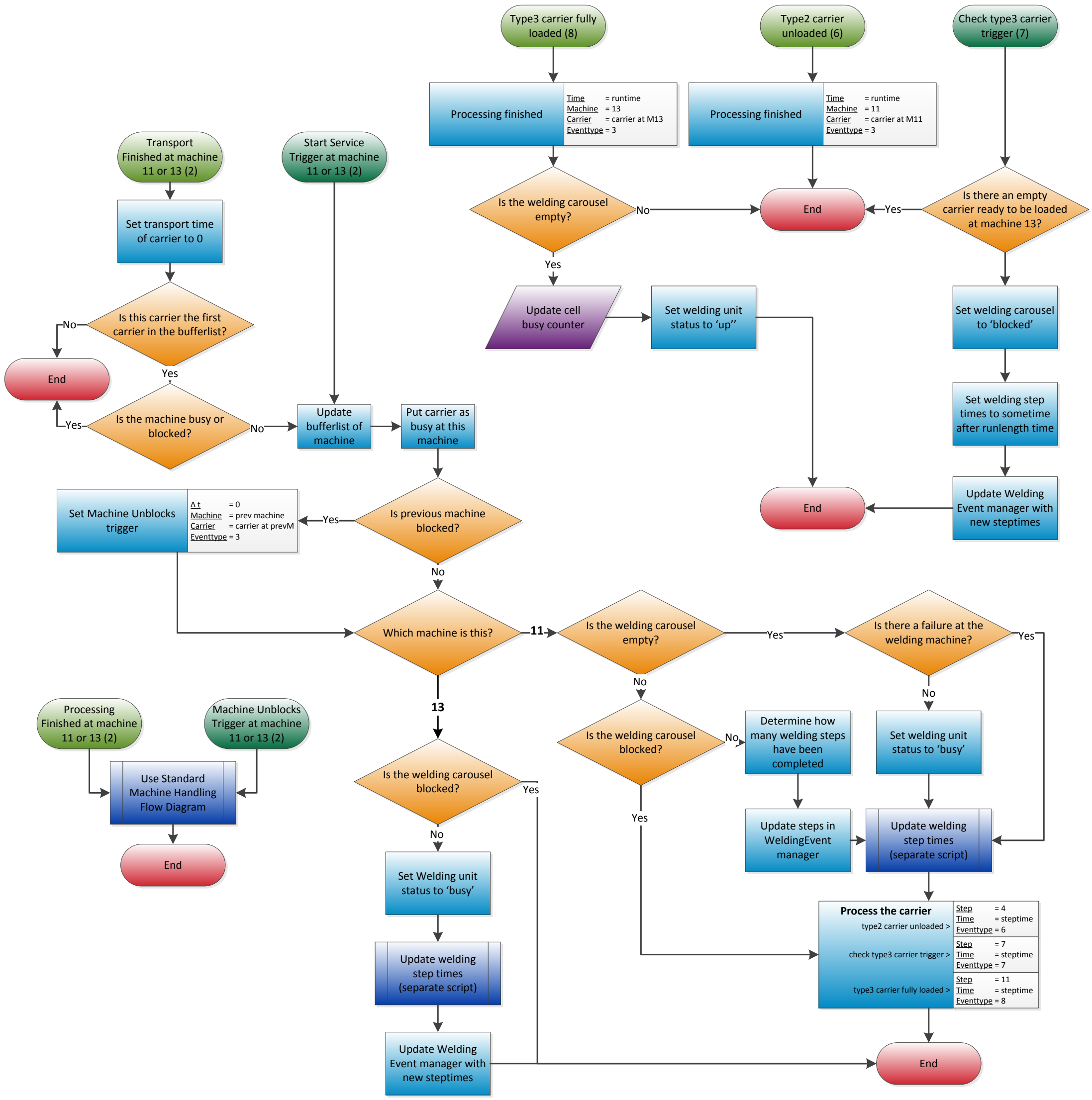

Figure 19. Flow diagram for handling events at the Welding Cell (third cell)

Appendix D - Distribution fitting

For the random variables Time Till Failure (TTF) and Time To Repair (TTR) of the production cells, the probability distribution functions are unknown. To estimate these distributions goodness-of-fit tests are done on data from production cells currently in use at Philips Drachten.

First, data is gathered from the information system on cell breakdowns. This is done for cells that have similar machines and similar MTTF & MTTR values. Data on MTTF and MTTR values are abundant. These values are calculated based on 40 weeks of data. Unfortunately specific data on TTFs and TTRs is very limited. The distributions are fitted on samples of 52 observations (each).

The tests that are performed are the Kolmogorov-Smirnov test (KS-test) and the chi-squared test (χ^2-test). The KS-test compares the constructed cumulative distribution of the sample (empirical distribution) to the theoretical distribution to which the sample is tested. The test statistic is the maximum difference between these two distributions. Using the Kolmogorov distribution, the probability of obtaining a test statistic at least as extreme as the one that is obtained is calculated (p-value). I perform this test at a significance level of 5%, meaning that if the p-value is smaller than 5% the hypothesis that the sample comes from the theoretical distribution is rejected.

With the χ^2-test, bins are created and the observations of the sample are 'put' into the bin that contains the value of that observation. Then the expected number of observations from the theoretical distribution that would fall in each bin (if a sample of the same size is taken) is compared to the frequency of empirical observations in these bins. The test statistic is calculated as: $\sum_{i=1}^{n} \frac{O_i - E_i}{E_i}$, where n is the number of bins, O_i is the frequency of the empirical data in bin i and E_i the frequency in bin i from the theoretical distribution. Using the chi squared distribution with n-1-par degrees of freedom, where par is the amount of parameters necessary to describe the theoretical distribution, the probability of obtaining a test statistic at least as extreme as the one that is obtained is calculated (p-value). If the p-value is smaller than 5% the hypothesis that the sample comes from the theoretical distribution is rejected.

The following distribution types are tested: Weibull, gamma, exponential, lognormal, generalized Pareto with 0 threshold and hyper-2 exponential with balanced means. At first, these distributions are tested with the maximum likelihood estimators for the respective probability distributions.

For the Time Till Failure:

	Weibull	Gamma	Exponential	Lognormal	Generalized Pareto	Hyper-2 exponential
p-value (KS)	14.7%	21.4%	1.6%	2.0%	3.7%	2.3%
KS-rejection	No	No	Yes	Yes	Yes	Yes
p-value (χ^2)	3.2%	14.0%	0.0%	0.0%	0.0%	0.0%
χ^2-rejection	Yes	No	Yes	Yes	Yes	Yes
H_0 rejected?	Yes	No	Yes	Yes	Yes	Yes

For the Time To Repair:

	Weibull	Gamma	Exponential	Lognormal	Generalized Pareto	Hyper-2 exponential
p-value (KS)	11%	6.6%	8.7%	69.0%	9.7%	6.6%
KS-rejection	No	No	No	No	No	No
p-value (χ^2)	1.3%	3.3%	3.3%	63.7%	1.7%	1.0%
χ^2-rejection	Yes	Yes	Yes	No	Yes	Yes
H_0 rejected?	Yes	Yes	Yes	No	Yes	Yes

The tests showed that for these theoretical distributions only the Gamma distribution fits for TTF and only the Lognormal distribution fits for the TTR. The sample means are different from the calculated MTTF & MTTR values. To compensate for this the fitted distributions are adapted so that the means correspond to the MTTF & MTTR values. The goodness-of-fit tests are again performed to see if these adaptations hold. The hypotheses are that:

- TTF of a production cell follows a Gamma(0.365 , MTTF/0.365).
- TTR of a production cell follows a Lognormal(ln(MTTR)-½*1.0641^2 , 1.0641).

	TTF ~ gamma	TTR ~ lognormal
p-value (KS)	17.6%	43.2%
KS-rejection	No	No
p-value (χ^2)	10.0%	46.1%
χ^2-rejection	No	No
H_0 rejected?	No	No

The hypotheses that the observations come from these distributions are not rejected and so these distributions can be used in the simulation model.

Appendix E – Model validation

In order to validate the simulation model, a similar production line that is currently in use at Philips Drachten is simulated.

The model is altered in such a way that it reflects the similar production line that is currently in operation at Philips Drachten. The results of the model are then compared to real life results. Unfortunately, no production line exists which contains an external buffer like the one in between Cell 1 and Cell 2. Also, no production line exists that has fully automated coupled carrier loops.

The production line that is used for this validation consists of 5 cells and has 2 machines in each cell, giving a total of 10 machines. There is one carrier loop and one place where products Fall Off. Each cell has breakdowns and repairs in the same manner as the assembly line. Four of the machines have unifeeders and thus stochastic processing times.

Data from 100 shifts is gathered from the information system of Philips Drachten. Each shift lasted on average 20244 seconds (about 5.6 hours). On average the production line produced 4208 products per shift.

The model I created does not allow for variable shift lengths. So the performance measures that will be compared are the average production rate (products produced per hour). The real production line has an average production rate of 750 products per hour with a 95% confidence interval of [731-768]. The simulation is now run for 100 shifts of 20244 seconds. The results from this simulation show an average production rate of 742 products per hour with a 95% confidence interval of [725-758].

I perform a 2 sample Kolmogorov-Smirnov test and a two sample t-test. These tests are performed using the available Matlab functions. The tests are both performed with a significance level of 5%. The two sample Kolmogorov-Smirnov test does not reject the hypothesis that the real production data and the simulation data come from the same distribution. The two sample t-test does not reject the hypothesis that the real production data and the simulation data come from the same normal distribution.

From this I conclude that the model can simulate a real production line.