INCREASING THE PRODUCTIVITY OF PRODUCTION LINE 52 BY USING THE TOC

A Case Study at Heineken Zoeterwoude

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Preface

After months of hard work, I am proud to present my thesis for the Industrial Engineering and Management bachelor. During the internship period, I have learned many skills and gained knowledge, particularly about the simulation process and working for a multinational company as Heineken. I would like to give special thanks to a few people who made this internship possible or helped me significantly with my research.

My bachelor assignment started at the beginning of the COVID-19 health crisis, which made communication and obtaining the required information more challenging. I want to thank my Heineken supervisors Teeuwen and Eric Kögeler for continuing the assignment and providing all the help I needed even in these unpredictable and demanding times. I would like to thank Martijn Mes for his valuable and critical feedback.

Furthermore, I would like to thank my girlfriend Eliza de Vos, who supported me during the harsh times with my ailing mother. She also helped me to correct grammatical errors and to use the correct referencing style.

I would like to thank my friend Rutger Habets who did a similar bachelor assignment at Heineken Zoeterwoude for helping me to find the right contact person for the internship and solving some simulation errors with me.

Lastly, I want to express my gratitude to the operators of production line 52, who went the extra mile for me. They did not only help me to find the answers to my questions but also put much time and effort to help me understand the production line and its machines better.

Kind regards,

Diederik Willem Quak

Laren, August 2020

Management summary

Important note: The results of the experiments have been modified by a specific number, and some of the confidential data have been concealed in this version to protect the sensitive data for Heineken.

Purpose: This research assignment is a simulation study for possible improvements in production line 52 of Heineken Zoeterwoude. This production line fills and packages bottles with beer of different volumes. According to Raouf (1994), the current fast-moving global market demands the manufacturers to focus on cost-cutting, improving productivity levels, higher qualities and higher delivery reliability. This is also seen at Heineken. The improvements for the production line are focussed on increasing the productivity of the line to better deal with the increased competition and driving down costs. The Theory of Constraints method has been used throughout the report to find possible solutions for the production line based on the possible bottlenecks in the line.

The machines of production line 52 are subject to failures and can therefore not work all the time. These failures can cause other machines in the production line to become idle and thereby decrease the throughput and productivity of the production line (Ameen, AlKahtani, Mohammed, Abdulhameed, & El-Tamimi, 2018). Heineken makes a distinction between two types of failures: short and long stoppages. Short stoppages are failures that took shorter than five minutes to repair, while the long stoppages took five minutes or longer to repair. The idea behind this distinction is that the line layout can decrease the productivity losses caused by short stoppages with buffers, but that long stoppages take too long for prevention that machines become idle in the system. Since this research focusses on improving the line layout to increase the productivity of the line, only the short stoppages are taken into account for the improvement of the production line.

Solution design: Heineken uses the metric Operational Performance Indicator No Order No Activity (OPI-Nona) to measure the productivity levels of the production lines. Since this research is focussed on increasing the productivity of line by decreasing the idling losses caused by short stoppages, the metric Operational Performance Indicator Operation Time (OPI-OPT) has been chosen to measure the productivity level of the experiments. The metric OPI-OPT measure the productivity level of the line by only taking the short stoppages into account. The average OPI-OPT value for the first half-year of 2020 was 81,01%.

De Vries (2019) found that the current workload allocation model that is used for production line 52 may not be optimal. She used the models described by Craighead, Patterson, and Fredendall (2001). These are the bowl, peak, sawtooth, reverse sawtooth and the peak model. De Vries found out that implementing the sawtooth and peak model increases the productivity of production line 52. This thesis assignment builds upon the findings of the work of De Vries (2019). The experiments of the solution design are based on a combination of the workload models and the possible bottlenecks.

Buffers are used to deal with the variance of the operation times of machines. Buffers are able to increase the throughput and thereby productivity of the production line by limiting the propagation of the distributions, but at the expense of additional investments, floor space and inventory costs (Amiri & Mohtashami, 2012). The effects of extra buffer placement for production line 52 is also investigated in this research. Two types of experiments are conducted to evaluate the effect of an increasing buffer amount for the productivity: an overall buffer increase and an increase in buffer amount in front of selected machines.

Stochastic variation has a profound effect on the productivity of the line. The effects of a reduction in the time needed to repair the machine failures or reduction in the number of failures have been evaluated. Different scenarios for the reduction of failures and failure times have been tested for each machine. These experiments are used to advise on what machine Heineken should focus for reduction of failures.

Simulation model: Production line 52 is simulated in Plant Simulation from Siemens for the evaluation of the experiments. The control panel of the simulation model is displayed in Figure A. The control panel of the simulation model has been divided by function. The green area shows the methods that are used for the logic in the simulation model. The data used for the validation and the input of the experiments are located in the light blue area. The experiments are conducted with the experiment managers in the orange area. Each of them is used for a different experiment. Lastly, the material flow and production line are located in the dark-blue area.

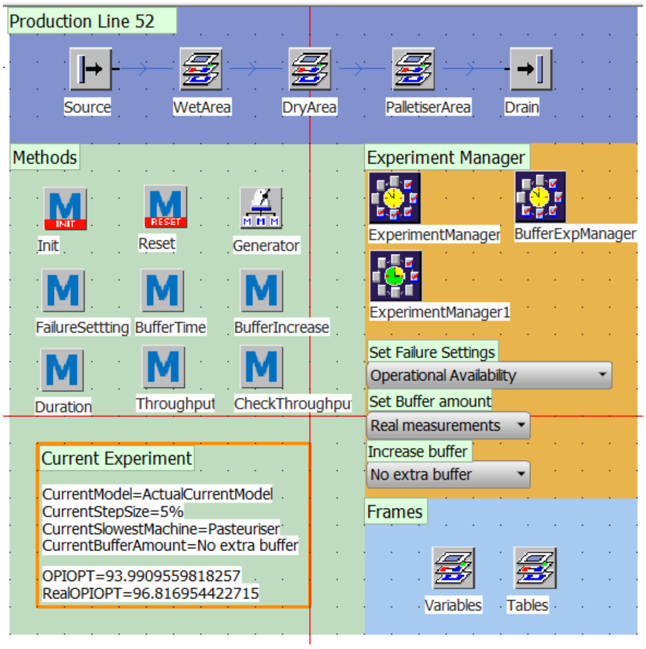


Figure A: Control panel of the production line

The production line has been split up in three parts to obtaining a good overview of parts of the production line. The dry area is the second part of the line and visualised in Figure B. The production line has been modelled based on real data of the line. The following input data has been used for the simulation model based on real measurements of the line: buffer sizes, the processing speed of the machines, failure behaviour of the machines and speed of the buffers. I have tried to model the parts of the production line in such a way that it corresponds with the layout of production line 52.

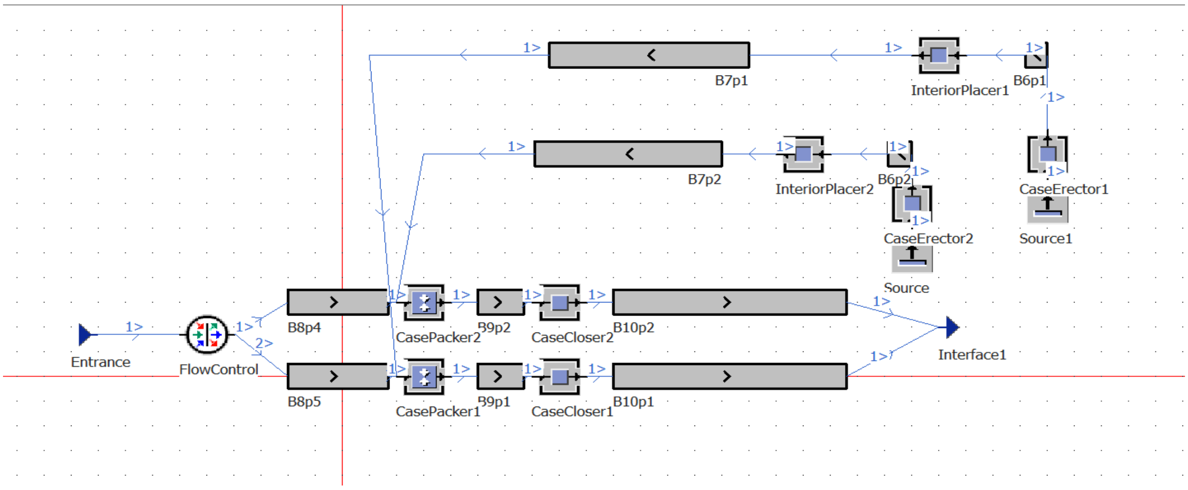


Figure B: Example of the layout of the simulation model

Results: In Table A, B and C the results of the best experiments for each experiment type are shown for the workload models, buffer and failure experiments, respectively. The cost and benefits of the solutions are based on X years since Heineken only implements improvements when the investment can be earned back within X years. The advice for Heineken is based on the return of investment in X years. The cost and benefit for the implementation of the solution have been concealed since this is confidential information.

Table A: Cost-benefit for best settings for the workload models for X years

Workload model	OPI-OPT increase (%)	Cost (€)	Benefit (€)	Profit (€)
Bowl	0,73			
Peak	1,24			
Sawtooth	0,57			
Reverse sawtooth	1,14			
Levelled	-1,67			

Table B: Cost-benefit for best buffer experiments for X years

Buffer	OPI-OPT increase	Cost (€)	Benefit (€)	Profit (€)
30% Overall buffer increase	1,71			
30% More buffer case packers	1,20			

Table C: Cost-benefit for best failure reduction experiments for X years

Failure	OPI-OPT increase	Benefit (€)	Profit (€)
50% Reduction failures case packer	1,21		
50% Reduction failures CPL	0,92		
50% Reduction failures case erector	0,75		

The peak model showed the most increase in OPI-OPT and profit for production line 52. This workload model experiment showed an increase of 1,24% of the OPI-OPT in comparison with the current model. The cost for implementation of the workload models is estimated at X euros to change the speed for all the machines. The machines are capable of producing at the speed of the model but need a one-time software change to do so. It is calculated that a 1% increase in OPI-OPT increases the profit of Heineken with X euros per year. The peak model results in an extra profit of X euros over X years.

It should be noted that the effects of increasing and decreasing the production speed on the wear and tear of the machines are not included in the analysis. When the amount of failures increases because of the machine have a different processing speed, the peak model may not be profitable anymore. The workload models showed to perform better than the current model in the simulation of this research but to a lesser extent than was shown by De Vries (2019).

Increasing the buffer amount in front of the machines is a costly investment. The costs for increasing the buffer amount in front of all the machines is therefor not advisable since the payback period is too long for Heineken. Increasing the buffer capacity in front of the case packers may be an appealing option for Heineken since this solution generates profit within X years for Heineken according to the simulation. The buffer experiments showed to be a less profitable solution than implementing the peak workload model for production line 52 for the first X years of implementation. Increasing the buffer amount in front of the machines will, however not result in a change to the wear and tear of the machines. Therefore, the effects of the implementation can be better predicted. If Heineken expects that the wear and tear of the machines will increase significantly with the implementation of the proposed peak workload model, increasing the buffer capacity of the case packers may be a safer bet.

The failure experiments showed that there is little difference between decreasing the time to repair by half or decreasing the number of failures by half for the increase in productivity. The machines that showed the highest productivity increase when the number of failures was halved were the case packers, CPL machines and the case erector. These experiments were conducted to show Heineken what the most critical machines are to reduce the number of failures for the productivity level of the line. The cost of decreasing the number of failures is not known but could be investigated in further research.

Conclusion: The experiments showed possible areas of improvement for the production line. The choice for improvement is based on the risk tolerance of Heineken and the practicability of the solution. It may be interesting for Heineken to investigate how they can decrease the number of failures or repair times for the case erector, CPL machines and case packers to increase the productivity of the line significantly. Implementing the peak model results in an extra profit of X euros, increasing the buffer amount in front of the case packer generates an extra X euros and reducing the number of failures of the case packers result in a profit of X euros in X years.

Contents

List of abbreviations

Abbreviation	Meaning
CPL	Bottle labelling machine
DBR	Drum Buffer Rope
DES	Discrete Event Simulation
KPI	Key performance indicator
MER	Mean Effective Rate
MES	Manufacturing Execution System
MSER	Mean Standard Error Rule
MST	Mean Stoppage Time
MTBA	Mean Time Between Assists
MTBF	Mean Time Before Failure
MTTR	Mean Time To Repair
OEE	Overall Equipment Efficiency
OPI	Operational Performance Indicator
OPI-Nona	Operational Performance Indicator No activity no order
OPI-OPT	Operational Performance Indicator Operational Time
PLC	Programmable Logic Controller
TOC	Theory Of Constraint
SMED	Single Minutes Exchange Die
TPM	Total Productive Management
WIP	Work In Process

Definitions

Assist - The repair of an internal failure that takes shorter than five minutes.

Autonomous preventive maintenance - Operators have the responsibility to do maintenance to the machines they are responsible for regularly.

Buffer capacity - The maximum number of products that a buffer can hold.

Buffer time - The amount of time that a buffer a machine can operate if a failure has occurred elsewhere on the line.

Downstream - Stations that exists before the bottleneck machine in the line.

Equipment - A part of the production line that is directly responsible for the packaging of the bottles.

Failure - A machine stoppage that took longer than 5 minutes to repair.

Station - Group of machines that have the same production function as, e.g. the filling of beer in the bottle.

Fill level - The percentage of the buffer maximum buffer capacity reached.

Machine - Equipment, but on a higher level. The different machines are indicated in Figure 3.

Nominal production speed - The set production speed for a machine.

Protective capacity - Processing speed that is higher than the bottleneck machine. A higher processing speed makes it possible that buffers can recover to nominal levels if a failure has occurred.

Recover time - The amount of time that is needed to restore the buffer amounts on the buffers to the desired configuration of buffer amounts over the line. In the case of the V-graph methodology, this is to have full buffers upstream and just enough WIP on the buffer downstream to ensure the machine downstream have enough WIP to work on their set capacities.

Upstream - Stations that exists after the bottleneck machine.

1

Research Introduction

This chapter presents the research problem, the context in which the research is conducted and the solution approach. This chapter acts as an introduction to the research. The rest of the report follows out of this chapter. This thesis assignment is conducted at production line 52 of Heineken Zoeterwoude and focusses on the improvement of the line. An introduction to Heineken and Heineken Zoeterwoude is given in Section 1.1 to get a better idea about the company at which this research is done. Section 1.2 explains the current difficulties that the manufacturing and beer market are experiencing to understand the current difficulties of the branch better. The next section focusses on the identification of the research problem in the light of the current beer market and the specific problems that are seen for production line 52. Section 1.4 shows the research design, which is used as the blueprint for the approach of this thesis assignment. Lastly, Section 1.5 presents the deliverables of the thesis assignment.

1.1. Introduction Heineken Zoeterwoude

Heineken is an international beer brewer that was founded as a family-owned beer brewing business by Gerard Adriaan Heineken in 1864. Since then, the company has grown out to one of the biggest beer brewers of the world by revenue, second to only Ab InBev (Heineken N.V., 2020). Heineken is currently affiliated with over 300 brands and is the most international beer brewer in the world with sales in 190 countries over the world.

Three beer breweries of Heineken operate in the Netherlands. These are located in Wijlre, Den Bosch and Zoeterwoude. The research for this thesis assignment is conducted at Heineken Zoeterwoude. Heineken Zoeterwoude opened in 1975 and is the largest modern beer manufacturing factory in Europe with a capacity of 350 million litres beer production per year (Heineken N.V., 2020). Around thirty per cent of all beer that is manufactured at Heineken Zoeterwoude is used in the Netherlands. The rest is exported mostly to the United States of America.

Heineken Zoeterwoude is structured in several departments. An organigram has been made to get a better overview of how Heineken Zoeterwoude is structured, which can be found in Figure 1. Heineken Zoeterwoude has six departments. This assignment focusses on the packaging department. This department consists of 5 rayons which are only concerned with the packaging of the beer.

The focus of this research is on production line 52, which is part of rayon 3. Production line 52 opened in mid-2017 and is one of the newest production lines of Heineken Zoeterwoude. The line fills and packages non-recyclable beer bottles of different volumes. Non-recyclable beer is also named one-way beer since there is no return of the material. The production line can fill three different kinds of bottles. The bottles are boxed and shipped on pallets.

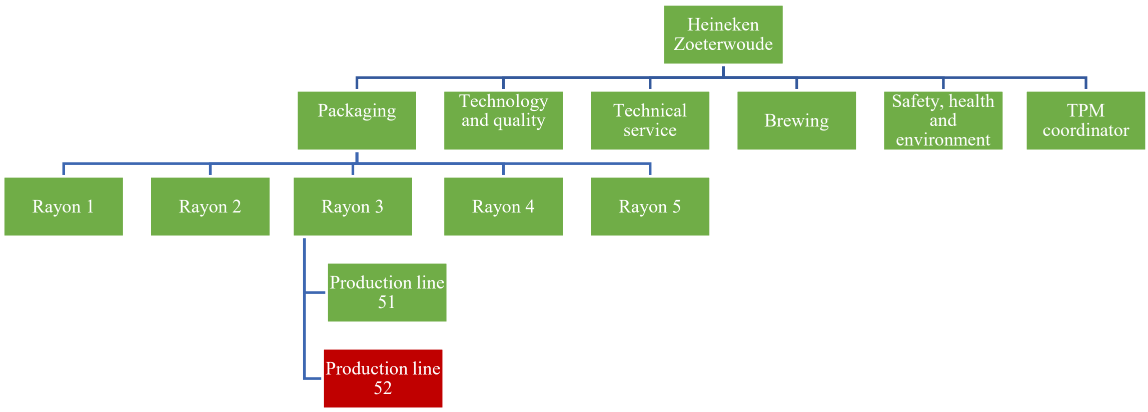


Figure 1: Organigram of Heineken Zoeterwoude

1.2 Context research

This section deals with the challenges in the beer manufacturing sector. This section first highlights the challenges which are seen for most manufacturing companies in general and then delves deeper into the specific challenges that beer manufacturers are facing.

The manufacturing environment has changed dramatically over the years. With the growing influence of globalization, manufacturers had to change the way they do business, and the pressure had increased to focus on high quality and high levels of productivity by reforming current work practices. Also, customer expectation has surged for the manufacturing as well as the service industry in this adaptive and fast-paced environment (Miyake, 1999). The current fast-moving global market demands the manufacturers to focus on cost-cutting, improving the productivity levels, higher qualities and higher delivery reliability (Raouf, 1994). Besides these challenges in the manufacturing industry, the beer industry is also facing its own challenges.

The beer market is seeing a trend in the countries with the most customers that customers are shifting from premium beers to craft beers and alternative beverages (Rutihauser, Rickert, & Sänger, 2015). Since craft beers and alternative beverages are often niche focussed, these do not rely on economics of scale, which is essential for brands as Heineken. For that reason, most international beer brands extended their assortment with new tastes and have increased the focus to decrease the cost to produce their premium brands.

Another challenge felt by most beer manufacturers has to do with distribution. Supermarkets and retail stores have become a more critical distribution channel than before. Supermarkets have in general lower profit margins on their products than speciality stores and pubs. To decrease inventory costs and increase the fulfilment rate, supermarkets are also demanding more frequent and flexible deliveries. This has led to a higher pressure to decrease the cost and to increase the flexibility for the premium beer brands (Rutihauser et al., 2015).

Additionally, premium beer manufacturers are required to focus on excelling in innovation. The competitiveness of the beer market has changed the industry to highly automated factories and increased the focus for innovation. Innovation is mostly used to acquire cost reductions, improved quality of the beer and an increased shelf-life (Kyselová & Brányik, 2015). This pressure for innovation not only holds for the innovation of the beer itself but also for organizational innovation (Rutihauser et al., 2015).

Beer manufacturers are under immense pressure to reduce their costs while at the same time, delivering high-quality goods and being more flexible. This is also seen by Heineken, which can be derived from their main strategy: stay ahead of the competition by driving innovation, increasing sales and minimizing costs (Heineken N.V., 2020).

To top it off, the ongoing health crisis of COVID-19 is forcing these companies to become more creative to ensure the operation of the business. The pressure to reduce costs and increase efficiency can become even higher when the virus leads to more uncertainty and unplanned costs. It is clear that the beer manufacturers are facing numerous challenges. This also holds for the Dutch biggest beer brewer at which this thesis assignment is carried out.

The information from this paragraph is visualised in Figure 2. It should be read as follows: the dark left part visualises the current market trends and challenges. The middle part denotes what should the companies should be focussing on to overcome these challenges and the green right part indicates what possible effects are of a successful implementation of the yellow part.

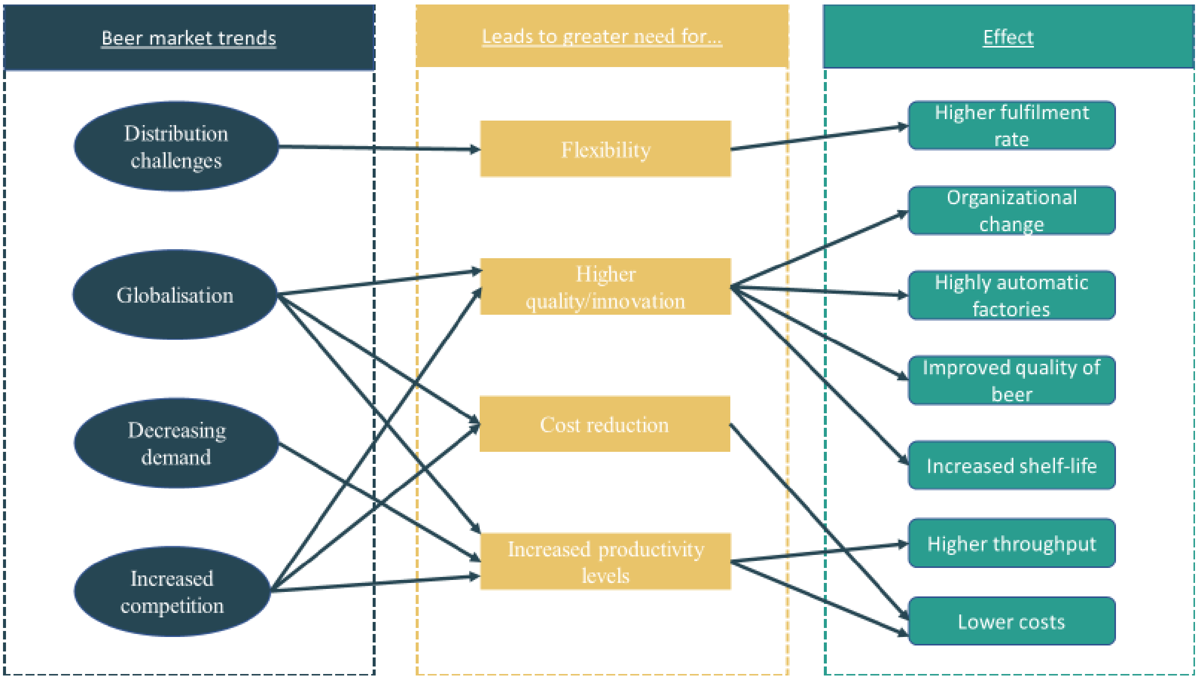


Figure 2: Visualization of the challenges and its possible solutions

1.3 Identification of the research problem

As mentioned in the context of research, the pressure to compete for large beer manufacturers is high for numerous reasons. Premium beer manufacturers have seen an increase in pressure to sell at a lower rate, becoming more flexible and striving for innovation.

Fleischer, Weismann, and Niggeschmidt (2006) state that competitiveness in the manufacturing sector can be defined according to the availability and productivity of their production facilities. With the increasing competition, it is critical for Heineken to achieve the highest possible performance of the production lines. In the current production systems that operate with high costs, small changes to the performance of the line can result in a high amount of saving in the long run (Lopez, 2014). The main interest of this thesis assignment is to save cost by increasing the performance of the production line, which is done by finding possible improvements in the productivity for the production line based on the Theory of Constraint methodology. This theory is embedded in the improvement strategy of Heineken and has become an important tool for practitioners to increase the productivity of a system by elevating the bottlenecks in the process (Şimşit, Günay, & Vayvay, 2014). The main research problem is defined as:

How to increase the productivity of production line 52 at Heineken Zoeterwoude by using the Theory Of Constraints?

The design of a production line is critical for the productivity levels of the line. Assigning the same production speed and buffers to all machines may seem the best option, but if the machine is not able to produce at equal speed and is variable in their processing time by, e.g., breakdowns, this is not feasible and optimal (Flores, Silva, Renelson, Sampaio, & Passos, 2016). A nonhomogeneous or unbalanced production line is a production line in which the servers differ in mean processing time or buffer quantity allocation over the line (El-Rayah, 1979; Ng, Shaaban, & Bernedixen, 2017). A balanced production line is a production line in which the production speed of all components is the same (Amiri & Mohtashami, 2012). Although it may sound confusing, unbalanced means that the workload or buffers are not evenly distributed over the line, but do try to increase the line's capability to deal with disrupting events and thereby create a more balanced throughput. Production line 52 is unbalanced since the assigned workload capacity of the machines over the line differ.

The investment and maintenance cost for most production lines is high, and therefore the design of a production line is of significant importance (Battaïa & Dolgui, 2013). It is, therefore, crucial to design the production line as good as possible to reduce the total costs and increase the performance of the line. In addition to this, Heineken focusses on becoming more sustainable. Improving the productivity of the line increases the efficiency of materials, energy used and the working hours of the employees, which benefits Heineken in their objective to become more sustainable in the future. The research of this thesis assignment focusses on improving the current design of the production line to increase the productivity of the line. Production line 52 is a so-called prio-line, meaning that is it easier to receive funding for investment in the line.

Production line 52 is subject to a high amount of variability because failures frequently occur, which have a profound effect on the behaviour of the line. Since the components of the system are interconnected and influence each other, it can be difficult to find exact results of possible solutions. Systems that are highly interconnected are said to have dynamic complexity. The system is said to be combinatorial complex if the amount of components of a system is high. Line 52 displays dynamic complexity and combinatorial complexity since the amount of components is high, and the machines are highly dependent on the output of the other machines. These complexities imply the following effects (Robinson, 2006, pp. 1-17):

- The action (solution) taken has different effects based on the chosen time frame
- Feedback between interconnected components of the line may result in counter-intuitive results
- Results of action may differ in parts of the production line or when compared to the performance of the line as a whole.

It may be challenging to predict the outcome of an action because of the issues mentioned above (variability, interconnectedness and complexity). Simulation provides the solution since simulation makes it possible to represent the three issues.

The most generic definition of simulation is the imitation of a system. However, since we are concerned with how the system behaves over time based on computational calculations the definition: "an imitation on a computer of a system as it progresses over time" is used (Robinson, 2006, pp. 2-3). There are several kinds of simulation techniques available. The Discrete Event Simulation (DES) is the technique that is used during this thesis. This simulation technique is mostly used for modelling operation systems at organisations (Mes, 2018). The main reason for the frequent use of the DES is that the simulation can be made visual and is relatively flexible. To profit from this flexibility, the method used to simplify the model should be appropriate (van der Zee, 2019).

Discrete event simulation is a modelling technique that shows how state variables change over set periods (Law, Kelton, & Kelton, 2000). A state is a set of variables that characterize a system on a specific time. An event is defined as a change in state value. DES only calculates the change in state that happens over time. In DES, entities move between activities that may or may not use a queuing system. The DES software Plant simulation from Siemens will be used for the modelling of the production line. This software is provided by the university and was already introduced in the bachelor program.

1.4 Research question design

Now that the relevance for research and problem definition are described, the research questions are presented. Research questions set the direction for the research problem and help to split up the management problem into smaller pieces (Cooper & Schindler, 2014, p. 89). Knowledge questions help in their place to answer the research question. This section is devoted to present the research question design and the approach that is taken to solve them.

1. How is the performance of production line 52 defined, and how can this be measured?
    a. What machines should be taken into account, and how does the line behave?
    b. What performance indicator is used to measure the productivity of the line?
    c. Which factors play a role in the productivity of the production line?
    d. What is the current performance of the line?

A thorough understanding of the production line is needed to be able to increase the performance of the line. This research question is answered in Chapter 2 and 3. In knowledge question 1a, an outline of the production line is given by considering the machines that need to included, and the most important properties are described to understand the behaviour and classification of the line. Knowledge question 1a helps to find improvement strategies in research question 2. This first knowledge question is answered by a combination of empirical research at the line and literature research.

In the next step, the indicators that are used to benchmark the results are investigated. The information comes from internal sources and interviews with employees of Heineken. These indicators are used to find the current performance of the line in knowledge question 1d, but also to benchmark the results of possible solutions. The performance of the production line can differ quite strongly over time due to improvements over time and unforeseen events. It is thus critical for a proper evaluation of solutions against the current line performance to carefully decide on the assessment of the current performance of the line.

Knowledge question 1.c delves deeper into the productivity of the line and seeks to find the factors that can influence the productivity level of the line. The possible factors are based on the Total

Productive Management strategy of Heineken and interviews with employees.

The last sub-question analyses the performance of the line with the help of performance indicator that was found in 1b. This is the pre-test of the simulation and used to have a general idea of the current productivity level.

2. How can the productivity of a production line be enhanced? Which of them are relevant for this research?
    a. Which strategies are used by Heineken to improve line performance?
    b. In what ways can the productivity of the line be increased according to literature?
    c. Which improvement technique is most suitable for the research of production line 52, and how can this be applied?

As explained in Section 1.4, this thesis assignment mostly focusses on improving the production line's capability to deal with disruptions caused by failures. This research question seeks to find suitable solutions for the improvement of the production line and is answered in Chapter 2. The first knowledge question investigates the strategy used by Heineken to increase the performance of the line. This is done to get a better overview of how Heineken improves their lines and how solutions are implemented. The next knowledge question focusses on finding strategies for line improvement according to literature research. The last research question investigates how the improvement techniques can be applied at production line 52 by taking the constraints of the system into account.

3. What information is needed for the conceptual model?
    a. What assumptions and simplifications have to be taken for the conceptual model and simulation?
    b. What data is required for the model?
    c. How can this data be captured?
    d. What is the output of the model?
    e. What experiments have to be taken?
    f. Does the model reflect the real system, and how can this be verified?

The production line is now demarcated, the productivity of the line is better understood, and possible changes for the production line are set into place. This research question fills up the gap of knowledge that is needed to create a conceptual model that acts as the blueprint of the simulation. The analysis of the input data for the conceptual model is shown in Chapter 3, while the conceptual model itself is discussed in Chapter 4.

Since it is not possible to perfectly imitate the real-life situation of production line 52 in a conceptual model or a simulation, simplifications and assumptions have to be taken; these are based on literature and advice of experts. Section 3b deals with the data that is required for the conceptual model. Section 3c investigates how this data can be captured. When this is put in place, the relevant data can be gathered. The fourth knowledge question deals with the output of the model.

The experiments are based on the findings of the second research question and discussions about the need for Heineken with my supervisor. Outcomes of the simulation are of little value if the simulation does not reflect the situation of production line 52 well. Consequently, we need to find ways to verify the validity and reliability of the outcomes and decide if we can accept the solutions as representative for reality. The experiments can now be run with the experiments determined in section 3e and the conceptual model. The results of the simulation are used for the next research question.

4. What advice can be given to Heineken based on the outcomes of the simulation study?

a. On what criteria should the advice be based?
b. What solution scores best on the criteria

For a proper solution choice, it is critical to know what the essential criteria are on which the solution is assessed. These criteria determine the choice for the best solution. The choice for the criteria is based on the supervisors of Heineken. Advice for the best solution is given based on the criteria. The results of the experiments and the criteria for the advice is located in Chapter 5. The advice itself is given in Chapter 6.

5. What steps need to be taken to implement the solution?

The proposed models will change the production line and thereby also change the performance of the production line. Several steps may be required to implement the solution successfully. The implementation steps are based on the implementation strategy that is used by Heineken, the people that need to get involved and the changes that have to be made. The implementation of the solution is provided in Chapter 6.

A visualization of the research methodology and approach is given in Figure 3. The grey boxes depict the knowledge questions for the research question. The knowledge and research question are written down in chronological order in approach. The outcome of each research question is used for the next research question. The result of the research question is shown in the green dotted circles.

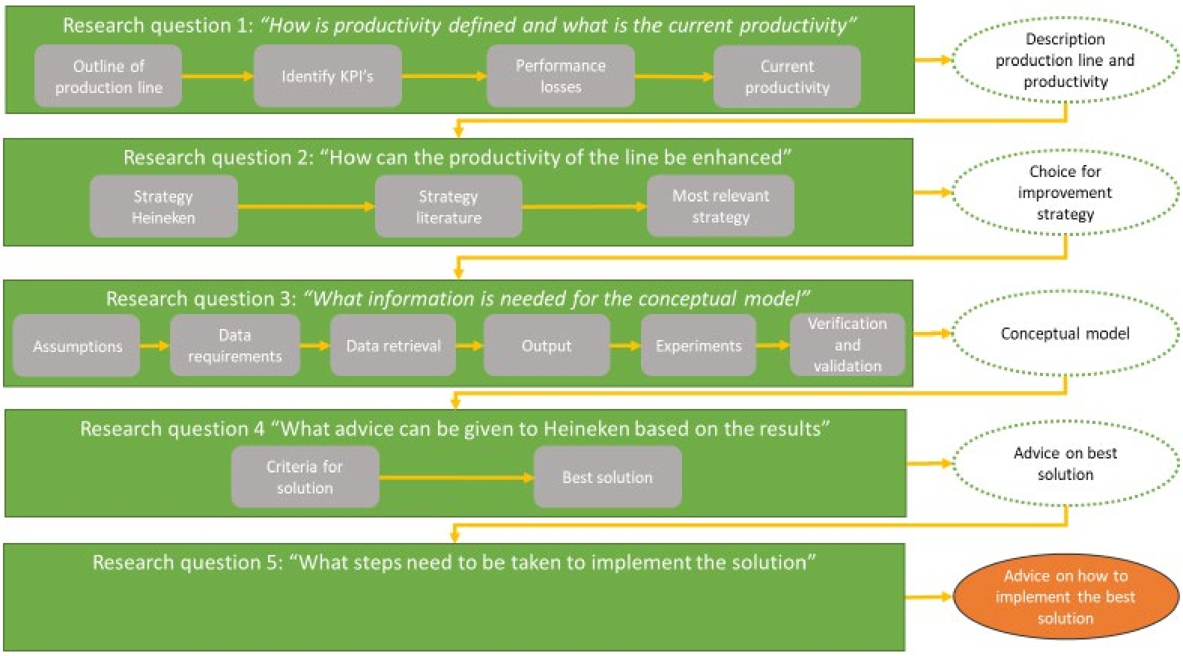


Figure 3: The research question design

1.5 Intended deliverables

The primary purpose of this research is to advise on possible improvements to unbalance the production line and the associated costs. The intended deliverables are meant to give a foundation for the consultation of the best solution. The intended deliverables for this thesis assignment can be found below.

- A conceptual model of the production line, which will mostly be used as a starting point for the simulation, but may be used for calculations or validation purposes. This conceptual model will be evaluated by the supervisor of Heineken and the university to check if this model accurately depicts reality.

- A simulation application of the production line together with an explanation for the basic understanding of the production line will be provided. With this, the model can be understood better, and adjustments can be made where needed.
- The results of the simulation study and the scoring of the results on the criteria list will be given. A general implementation guide for the solution will be given to ensure a smooth change to the proposed redesign of the line.

2

Theoretical perspective

This section suits as a general introduction to the possible solutions and demarcation of the research. First, a description of the production line is given. This description gives an overview of the outline of the production and what machines are included in the analysis. It also describes the most important properties of the line, which are the improvement strategy of Heineken is explained. Next, the improvement strategy that is used by Heineken Global is explained. Section 2.3 elaborates on the performance indicator that is used to measure the performance of the simulation model. This performance indicator is based on the philosophy of this management strategy. In Section 2.4, the effects of breakdowns on the whole production line are explained. The primary purpose of increasing the productivity of the production line is to increase the throughput of the system and decrease the total cost. Section 2.5 deals with the costs that are involved with the design of the production line. Lastly, possible improvements for the design of the production line are presented in section 2.5. These are based on the improvement strategy of Heineken Zoeterwoude, the Theory Of Constraints and the constraints of the production line.

2.1 Line description

In this paragraph, a description for the line is given by providing the outline of the line and describing the properties of the line's behaviour. The outline of the production line helps to give a better idea of how the production line works and what machines are taken into consideration for this research. This outline is given in Section 2.1.1. In the next section, the properties of the production line are given. This helps to understand the behaviour of the line and is used for the demarcation of the literature research for the optimal improvement strategies.

2.1.1 Outline of the production line

Production line 52 fills and packages non-recyclable bottles. The beer is brewed in the brewing department at Heineken Zoeterwoude and transported via a piping system into the packaging areas. The production line can fill and box three types of bottles that differ in shape and volume. The different volumes of the bottles are 250, 330 and 355 ml. Most often the bottles are packed in 24 piece boxes, but for 330 ml sometimes a 20 piece box is used. The production line is only able to fill and package one bottle type in one type of box at the same time, and adjustments need to be made to the system to be able to use a different bottle. This is called a changeover.

The maximum achievable production rate is around 80.000 bottles per hour since this is the production speed of the machine with the lowest speed. According to an operator of the production line, it takes at least around one and a half hour for an empty bottle to depart from the last step in the production line as described in Figure 5 of which the pasteuriser takes up 50 minutes. A distinction is made between several kinds of machines grouped in three sub-areas. These are the dry area, the wet area and the palletiser area. This study only covers the machines that are mentioned in the data collection system of Heineken since most information is available about these machines. Some of the machines are grouped since they are so tightly connected (e.g. the filler and rinse machine). Material that is needed for the machines of production line 52, but not considered in the scope of this research is the caps and the beer itself. We assume these items to be always available when needed so that it not constraints the production in any way. Line 52 depends on these products for production, but it cannot be controlled in this study and therefore falls out of the scope. The general production steps are explained below.

In the first step of the process, empty beer bottles arrive on pallets and are carried by forklift to the loading area. The pallet is defoiled by the defoiling machine and hereafter lifted to a higher level to the conveyor belt. Layers of the conveyor belt are pushed off the pallets and enter the conveyor to the filling machines.

The next steps have to do with the filling of the beer bottles. First, the bottles are cleaned to remove any residue that was still in the bottle. The beer is not produced at the production line itself but is transported by a pipeline from the brewing department to the packaging areas. The filler machine fills the empty bottles with the amount of beer that is appropriate for the volume of the bottle. Since oxygen in beer can decrease the shelf life, a water jet is briefly shot in the bottle that releases excess oxygen. The bottles can now be closed with a beer cap. The bottles are now washed, and quality inspection is done. These steps are grouped as the filling machine in the data registration system of Heineken, and therefore only the filler machine is shown in Figure 3.

The shelf life of the beer can also be increased by pasteurizing it. This is done in the next step to prolonging the shelf life further. The bottles are fed into the pasteurizer, which slowly heats and then cools the beers down. The heating is done by flowing hot water down the bottles, and consequently, the bottles come out wet out of the pasteurizer. The bottles are dried and go to the next step. The next part of the production line is also called the dry part of the line since no or little water is used for this last part of the line. The pasteuriser has the lowest capacity of the production line with 80.000 bottles per hour. Since Heineken has defined the bottleneck as the machine with the lowest machine speed, this machine is seen as the bottleneck.

The next part of the line has to do with the labelling of the products. This machine is also called CPL machine at Heineken Zoeterwoude. Three Heineken labels are added: one on the neck, one on the back and one on the front. There are four identical machines for each label, but only two at a time are needed. When the labels in the machine have run out, the other reserve machine is set into place to prevent losing any valuable time. The next step of the line is adding code with a laser. This code shows the date of when the beer was produced, the best before date and codes that are needed for the administration. The bottles are hereafter inspected and rejected if the product did not attain the required quality standards.

Before the bottles can be placed in the box, some pre-processing steps have to be taken for the box. This is done in the box lane indicated with a brown colour. Boxes arrive flat to the box line. Before they enter the internal production line, they need to be straightened out. A carton placeholder for each beer bottle needs to be put into the box to prevent the bottles from crashing into each other. Two types of boxes exist: 20 piece boxes are used only for 330 ml, and 24 piece boxes are used for all bottle sizes. The bottles are put into the boxes at the case packers. The last step of the dry area is to close the boxes. The closing is done by glueing the lids together.

The product is now ready for consumption but needs to be put on pallets for shipping. The boxes need to be put in a specific pattern to optimize the area space of the pallets. The boxes arrive individually on the conveyor belt to a machine that organizes the boxes in this pattern. This machine is called the palletiser. When one layer for the pallet is organized, the layer is placed on the lower laying pallet. When enough layers are put on the pallet, the pallet is sent to the foiling machine. The last step that is included in this research is the pallet labeller. This machine puts a label onto the pallet for administrative purposes.

For a visual overview of the production process, see Figure 4. The black lines depict the flow of the conveyor belt. Most steps consist of two machines with a corresponding conveyor belt, but in some places, the belts are united and split up again. This helps to ensure flexibility and continuity. The process begins with the infeed of empty bottle stacked on a pallet in the left upper side of the picture and ends with the pallet labeller.

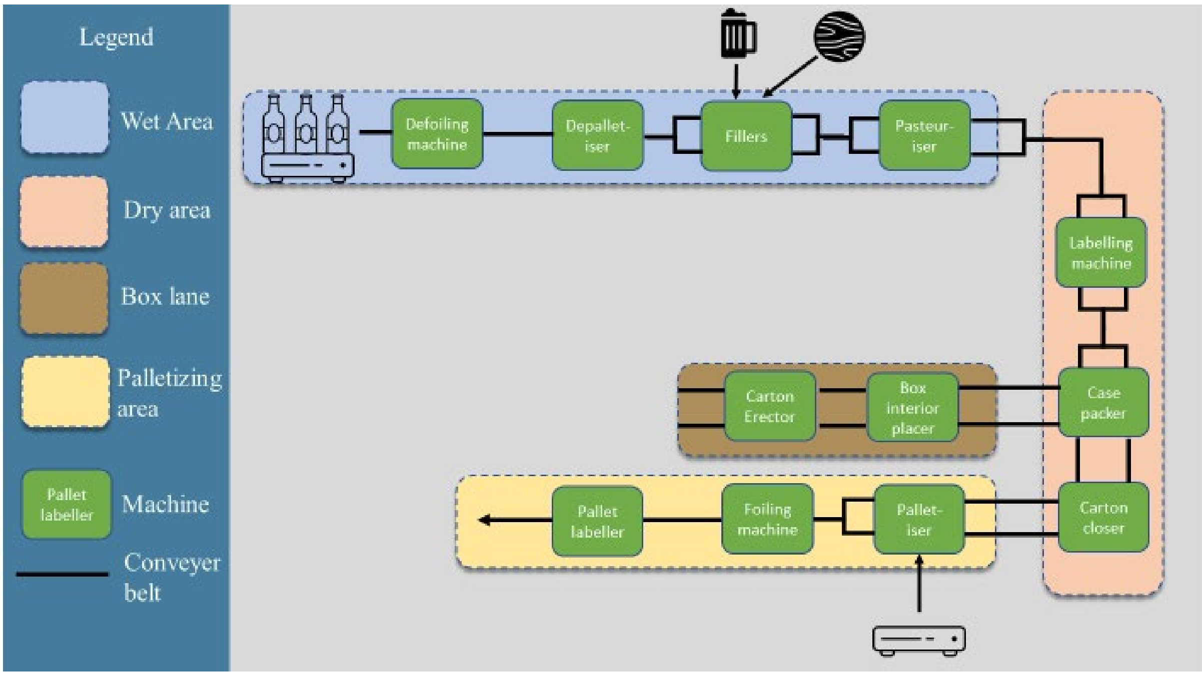


Figure 4:Portrait of the production line processes

2.1.2 Properties of the production line

Production lines have been an attractive approach for mass-production for a long time and still are today. Henry Ford pioneered the idea of the assembly line for the new Ford Model T in 1908. This model became a huge success and was so successful that Ford produced even more Model T's than all other models combined in the next 20 years (Alizon, Shooter, & Simpson, 2009). The first assembly lines, as proposed by Henry Ford, were rigid and straightforward in structure. Such a production line can be described as a strictly paced and straight single-model line. The range of used production lines has increased dramatically over time. Assembly lines have developed into a diverse range of kinds that can provide more flexibility (Becker & Scholl, 2006). Since each production line is different and has different characteristics, the production line should be appropriately defined to demarcate the core problem and find suitable improvements for this kind of production lines.

The description for the production line is mostly based on works of Battaïa and Dolgui (2013) and Boysen, Fliedner, and Scholl (2008). Battaïa and Dolgui (2013) laid down an extensive investigation in the taxonomy of production lines by studying over 300 studies on line balancing problems. Boysen et al. (2008) mention in their research that assembly line balancing (ALB) literature is often niche-focused and therefore made a framework to understand which type of production line is suitable for which ALB. The most relevant characteristics of these two works are explained and applied below.

- *The model of the production line*. A production line may be able to produce only one particular product, but could potentially also produce several kinds of products. If a production line can only produce one kind of product, then the production line can be described as single-model. If the production line produces several kinds of products, a distinction can be made between two kinds of models: mixed-model and multi-model line. In a mixed-model line, the type of producible product is alternated as needed, and no set-up time is needed. In a multi-model production line, products are produced in batches, and set-up time is needed before another product can be produced at the production line (Becker & Scholl, 2006). Production line 52 is a multi-model production line with the different types of beer bottles being the different products, while the beer that is used to fill them remains the same. The production line is only able to fill one type of bottle, and set-up time is needed before another bottle type can be filled and packaged in this production line. Figure 5 shows the visualization of the three different models.

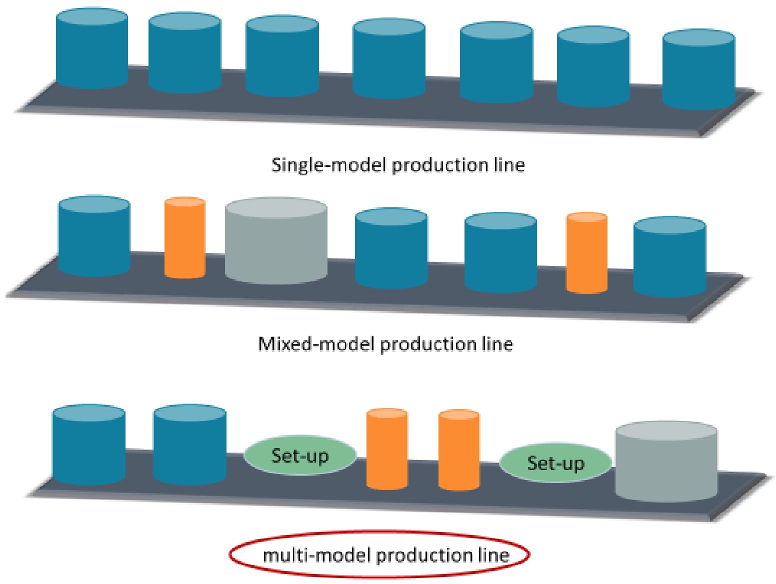


Figure 5: Different kinds of models for production line

- *Synchronous or asynchronous lines*. An asynchronous production line means that the products in the production line move sequentially between stations when the station is done processing, and the next station is empty (Lopes, Michels, Lüders, & Magatão, 2019). In a synchronous production line, the jobs are coordinated, and all the products move to the next station at the same time. Although a synchronous production line is, in general, less expensive than an asynchronous production line, it does not provide the flexibility asynchronous lines provide. Production line 52 is an asynchronous production line since the flow of products can be controlled (Lopes et al., 2019).
- *Paced or unpaced*. In a paced production line, there is a limited time that the machine and employees can work on the product in the station. The opposite holds for unpaced lines (Boysen et al., 2008). Almost all synchronous production lines are paced, while asynchronous production lines can be either paced or unpaced. Unpaced production lines can be set up and operated fast to provide the changing demands of the customers. The production line layout gives flexibility to the speed of the machines by letting them produce differently from the standard speed if this needed. Unpaced production lines are superior to paced lines for mixed-model production lines with a long line length (Öner-Közen, Minner, & Steinthaler, 2017).

The production line at Heineken is unpaced since the operators and machines are not restricted to a set amount of time for each task.

- *The reliability of the machines*. Reliability can be defined as the ability to carry out the tasks as expected (Nigel Slack, 2016, pp. 624-626). Unreliability increases the variability and complexity of the production line (Shaaban, McNamara, & Hudson, 2014) and is sometimes a bit overlooked issue of research (Hudson, McNamara, & Shaaban, 2015). Whenever the variance for the task time is sufficiently small, the station can be defined as deterministic and is thus reliable. This could be the case for highly automatic or easy tasks (Johnsen, 1983). If a production line is not reliable, this means that failures can occur and some tasks are not performed as planned. Since breakdowns frequently occur in production line 52, the production line can be described as unreliable.
- *The amount of buffer capacity*. Buffers are used to compensate for the variance of task times and can help to increase the line output of unpaced lines when the variability of the station is high. Variability has a significant impact on the performance of the production line, and Schmenner and Swink (1998) even state that the more random variability the process has, the less productive the operation is. A higher buffer capacity will increase the throughput of the machines in an unpaced asynchronous production line because it helps to reduce the effects of idling problems (Boysen et al., 2008; Smunt & Perkins, 1985), the concept of idling is explained in Section 2.3. Since production line 52 is an unpaced asynchronous production line, the optimal allocation of buffer quantity should be investigated during the simulation.

2.2 Total Productive Management

This section deals with the improvement strategy that is applied at Heineken globally. This helps to understand the work and business environment of Heineken Zoeterwoude. It also explains the use of the performance indicators and the theoretical perspective that has been applied during this thesis assignment. Total Productive Management is an adaption of the almost eponymous Total Productive Maintenance. First Total Productive Maintenance is explained in Section 2.2.1. Hereafter the Pareto-analysis and the Ishikawa diagram tools are explained in Section 2.2.2 and 2.2.3, respectively. These are tools that are used complementary to the Total Productive Maintenance strategy. Heineken puts a strong emphasis on breakdown reduction by performing a different kind of maintenance on the line. The different kinds of maintenance that are used by Heineken are explained in Section 2.2.4.

2.2.1 Total productive maintenance

Total Productive Maintenance originates from Japan, where Seiichi Nakajima developed it in the ’80s (Nakajima, 1988). Total Productive Maintenance focusses on improving the performance of a production system by reducing the production losses. According to Total Productive Maintenance, a production line can be improved by reducing the negative effect of the production loss on the production line. Venkatesh (2007) coined Total Productive Maintenance as the medical science of a production line because the main focus of the paradigm is to prevent breakdowns and gives guidelines on how to maintain the machines best. In this way, the machines are staying “healthy” for a more extended time. Total Productive Maintenance emphases that substantial attention is needed for the equipment of the production facility.

Total Productive Maintenance not only describes possible areas of improvements, but it also sets a standard on how to improve those areas of improvement and targets to achieve increased production and job satisfaction at the same time. Total productive maintenance stresses the importance of maintenance. It prescribes that it should not be seen as a non-profit activity and should be integrated as an essential part of the production process (Venkatesh, 2007). Total Productive maintenance is based on three concepts: maximize equipment effectiveness (more on this in Section 2.3.1), autonomous maintenance by operators and activities in small groups (Ljungberg, 1998).

One of the unique features of Total Productive Maintenance is the ownership of the machines by operators. Operators are the owner of the equipment of the production line and are thereby responsible for the performance of it. This distinct characteristic helps to give the operators a feeling of involvement. Operators have to routinely do preventive maintenance for the machines to increase the time before the machine breaks down (Ahuja & Khamba, 2008, p. 14). Total Productive Maintenance goal is to decrease the need for maintenance and to achieve zero losses and zero defects (Digalwar, Abhijeet K., Nayagam, Padma V, 2014). This leads to a higher production rate, cost reductions and increased productivity (Nakajima, 1988).

2.2.2 Pareto-analysis

The Pareto-analysis is a tool often used by Heineken to find the most critical areas of improvements of the line. For most of the machines, most of the failures are caused by a small number of errors. This is in accordance with the Pareto law, which first noted that 80% of the wealth in Italy is owned by only 20% of the population (Kenton, 2019). In manufacturing plants, it is also often seen that 80% of the breakdowns are caused by 20% of the most occurring failures. This tool is often used for the problem-solving in manufacturing. The method indicates the most critical areas of improvement by indicating the most occurring errors. The root causes of the errors are investigated to find ways to improve the performance of the machine (Lande, Shrivastava, & Seth, 2016).

2.2.3 Ishikawa diagram

The fishbone or Ishikawa diagram is an often-used tool to identify the cause and the effects of the studied issue (Coccia, 2017). The organizational theorist Ishikawa introduced this concept in 1960 for the quality management of ships. Since the diagram resembles the bones of a fish, the term fishbone diagram was coined. The studied effect is placed on the right side of the diagram, while the causes grouped in subdivisions are portraited with arrows on the left side. Often the old-fashioned subdivision is used: machines, workforce, materials, money and methods. The creator of the diagram is, however, free to choose whatever heading for a cause subdivision he wants (Slack, Brandon-Jones, & Johnston, 2016). This fishbone diagram includes workforce, machinery, material and method for the productivity losses of the line—the sections below elaborate on each division. Figure 6 visualises the causes that lead to production losses at production line 52.

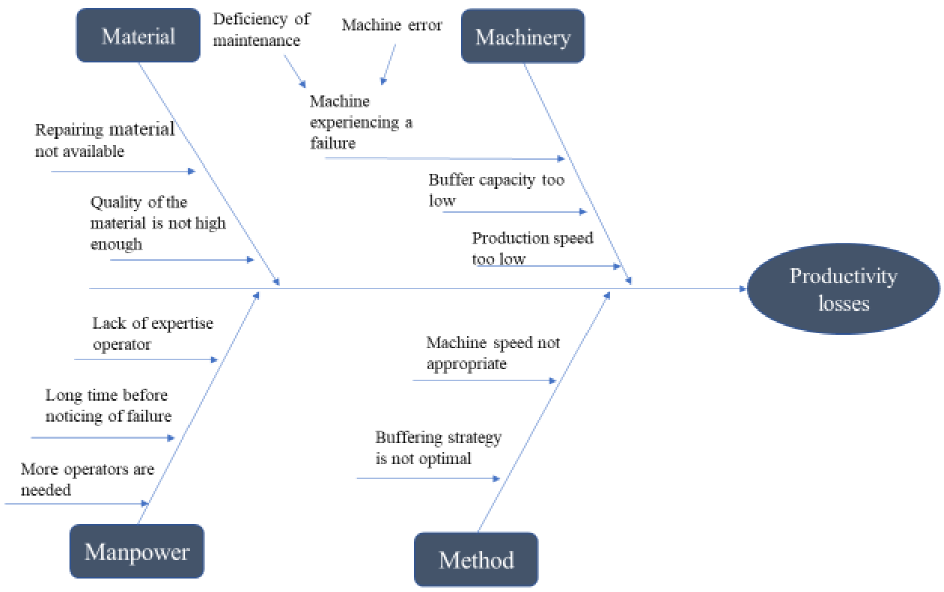


Figure 6: Fishbone diagram for the productivity losses of line 52

The possible causes for productivity losses for each of the four areas are explained in more detail below. These are based on interviews with operators and the theoretical framework and empirical findings.

- *Material*: When a failure has occurred, material may be needed to bring the machine back to be able to operate again. When there is not enough material or if this material is not of good quality, this may affect the repairing time or the time before the next failure.

- *Machinery*: The machinery includes all components that are part of the internal production line, as explained in Section 2.1.1. The foremost reason for the losses of productivity as can be seen in Figure 6 is the effects of machine failures to idling in the line. This directly links to the failures and unreliability of the machines. Failures can be prevented or delayed by maintenance and proper handling of the machines. The machines should, therefore, get enough maintenance to maintain healthy for as long as possible. Heineken has implemented several forms of maintenance, as explained in Section 2.2.4 to reduce the effect of failures of the machines.

  The design of the line also has a significant effect on productivity losses. Buffers are set into place to increase the ability of the line to deal with the unreliability of the line. If this is not sufficient idling can happen which decreases the uptime of the machines. The production speed of the machines can be a limiting factor for the productivity of the line. The production speed determines the speed of which parts are placed from one buffer to the other buffer and therefore influences the effects of idling on the line.

- *Manpower*: Almost all of the stops in the production line need to be fixed by operators of the line. This could be easy and short assists in problems that could take for a prolonged time. The time to repair is based on three factors: the number of operators available, the experience of the operator and the time it takes before the operator notices the problem.

- *Method*: The unbalancing method the buffering strategy is used to increase the productivity of the line and reduce the effects of idling. The production speed, according to this method and the amount of buffering before the machines determine the performance of the line. The improvement techniques, as explained in Section 2.5, try to increase the performance of the line by optimal allocation of production and buffer capacity per machine.

2.2.4 Types of maintenance

TPM stresses the importance of maintenance to keep the production line healthy. Several types of maintenance protocols can be distinguished. The types of maintenance are presented in increasing level of failure avoidance (Venkatesh, 2007).

- *Breakdown maintenance*. The most basic form of maintenance. If this maintenance strategy is applied, maintenance and repairing are only done when the equipment has failed.
- *Preventative maintenance*. The daily maintenance that helps the machinery to keep in a healthy condition by inspecting and minimizing the effect of deterioration. Preventive maintenance can be further split up in periodic maintenance and predictive maintenance.
- *Periodic Maintenance*. is the act of inspecting, cleaning and servicing routing work every set amount of time to prolong the machine lifetime and delay failures

- *Predictive maintenance*. Inspection and diagnosis help to predict the service life of machinery. Heineken uses an instrument that measures the vibration of the machines to predict the condition of the equipment.
- *Corrective maintenance*. By redesigning and replacement of equipment, the failure rate may decrease.
- *Maintenance prevention*. The machinery is regularly inspected on weaknesses. Based on the weaknesses that are found that could lead to breakdowns, an action is taken.

The first record for the use of maintenance prevention was in 1960 by the company Nippondenso. The job of maintenance prevention was assigned to special maintenance personal. As this increased the total personnel hired by the company and thereby increased the cost, the company looked for cost reduction of maintenance prevention. They found out that routine inspections and corrections of the equipment should be done as part of the schedule of the operators. This became an integral aspect of Total Productive Maintenance and is called autonomous preventive maintenance, meaning that the employees are responsible for the continuation of the production line, including the prevention of breakdowns. This also makes one of the main differences between Total Productive Maintenance and other business strategies. The autonomous preventive maintenance part makes the operators responsible for the performance and breakdowns of equipment of the production line. It thus results in a feeling of involvement by the employees (Venkatesh, 2007). Not only operators but people from all levels of the organisation should be involved in the performance of the production line.

2.3 Performance indicators

This section deals with the performance indicator that is used during the thesis, which is based on Total Productive Management. The most important metric that is used by Heineken to measure the productivity of the production line is the Operational Performance Indicator (OPI), which is also known as Overall Equipment Efficiency (OEE). Only the term OPI will be used, which is the same as OEE to avoid confusion. Section 2.3.1 explains the main concept of OPI, while 2.3.2 delves deeper into the productivity losses that determine the value of OPI. Lastly, the exact choice for the metric is explained in Section 2.3.3.

2.3.1 Operational performance indicator

The pursue to maximize the productivity of a production line has led to the creation of rigorously specified performance indicators. An often-used metric for productivity analysis is Operational Performance Indicator. Performance indicators play an essential role in the improvement policy of TPM, and OPI may be one of the most critical performance metrics (Muchiri & Pintelon, 2008). This metric fits well into the TPM ideology since the metric decouples the losses of productivity and displays possible areas of improvement. This performance indicator OPI shows what percentage of the maximal possible capacity of the line is attained or how Williamson (2006) put it: the extent to what the equipment is operating as it is supposed to do. If the value of OPI for a production machine is 50%, that means that if the machine could have produced two times more products if it did not experience any failure or difficulties (Slack, Brandon-Jones, & Johnson, 2016).

Production line 52 is only set to run when there are enough orders for the product. OPI assumes that all time can be used for production. This is not achievable and even desired since the demand is not high enough to produce all the time and time is reserved for changeovers, cleaning and other activities that are not directly related to production. The metric Operation Performance Indicator No order no activity (OPI-Nona) only takes the time that the production line should produce into account. The productivity of the line is based on the effective working time. This is the time that the line should run. The metric OPI-Nona is the most used variant of OPI to accurately measure the performance of the production line at Heineken Zoeterwoude.

The value of OPI-Nona is based on three factors. These are quality, availability and performance (Muchiri & Pintelon, 2008). These factors together determine the productivity level for OPI-Nona. Each factor is measured in the resulting value divided by the maximum value that could be attainted at maximum. The factors need to be multiplied to find the correct value of OPI-Nona. It could be possible that equipment scores high on two of the three factors but low on the remaining factor, and thereby the equipment has a relatively low OPI Nona. The formula to calculate the value of OPI-Nona is provided in Formula 1 below.

$$OPI\ Nona = Availability\ \times Performance\ \times Quality \tag{1}$$

The composition of OPI is visualised in Figure 7 below. The good product production time is the output of good products in a time frame divided by the number of products that could at maximum be produced by the system. OPI determines the maximum possible throughput over time based on the manned time, while OPI-Nona calculated this value based on the effective working time.

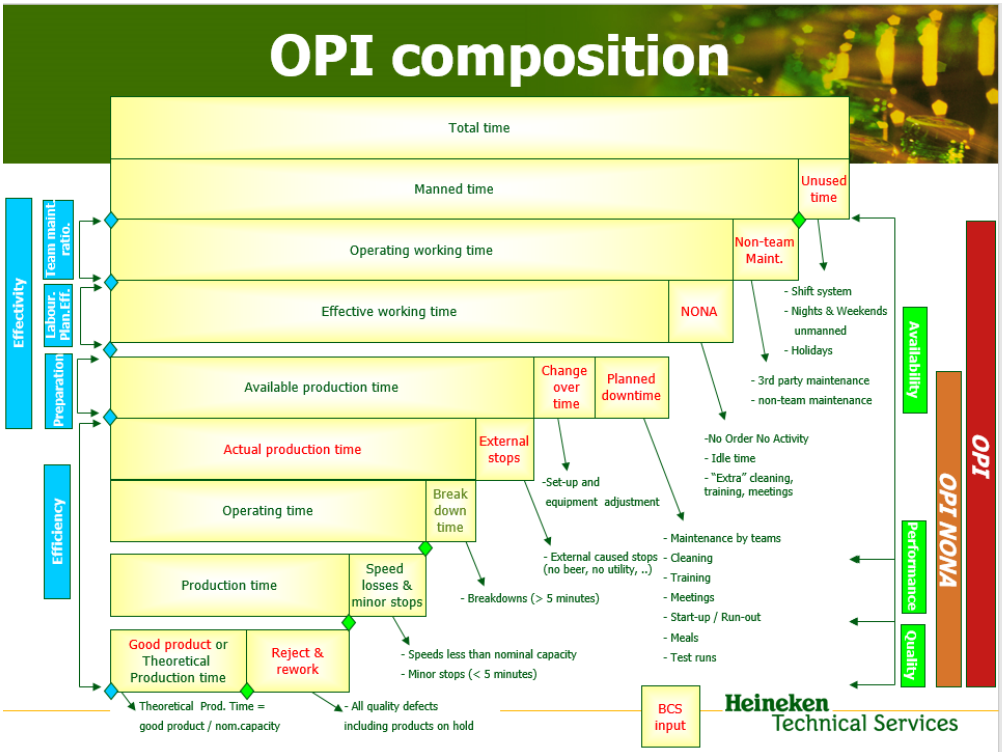


Figure 7: The composition of OPI and OPI-Nona (Heineken N.V., 2020)

The productivity losses of OPI-Nona as visualized in Figure 7 can be divided into roughly three areas of improvement. These losses are based on Muchiri and Pintelon (2008).

- *Availability* indicates how much of the available production time is truly spent on production. Planned downtime and changeover time reduce the value of availability. Changeover time is the time needed to change from one bottle type to another. The shorter the time needed for the changeover, the more time can be devoted to production. SMED is a methodology from lean to decrease the time needed for changeovers of the production line. Planned downtime is the time that is needed to fix the machines of the line that was planned. Autonomous preventive maintenance can keep the machines in good shape and thereby reduce the need for planned downtime.

- *Performance* indicates which percentage of the maximum possible speed was attained for the machine or whole production line. It may be possible that a machine is not able to produce at the set speed. Speed losses, breakdowns, minor stops and idling influence the value of the performance part of OPI-Nona. If a machine is for some reason not able to produce at its set speed, it causes a speed loss.

  Heineken makes the distinction between short and long stops. A short stop is defined as a stop that takes shorter than five minutes to repair. Long stops take longer than five minutes to repair. The idea behind this distinction is that the design of the production line could help to reduce the effects of short stops on the performance of the other machines, while this is much more difficult to do so for long stops. Idling is the occurrence that a breakdown of one machine causes another machine in the line to stop producing. This phenomenon is explained in more detail in Section 2.4. A performance level of 100% means that the equipment is running at its maximum possible speed.

- *Quality*. If products did not meet the quality requirements or broke down during the production, the item needs to be discarded or repaired. The Quality component of OPI-Nona indicates the number of products that meet the quality requirements.

The capacity of the bottleneck machine limits the maximum productivity of a production line since this machine constraints the production speed of the whole production line (Goldratt & Cox, 2016). Therefore the analysis is often done to increase the utilization and OPI of the bottleneck machine and thereby to increase the production speed of the whole production line.

An OPI score of 100% means that the production line is producing only good products, with no failures and with no time needed for required planned events. Most manufacturers have an OPI of around 60%. An OPI of 85% is perceived as a long term goal for most manufacturers and is therefore named world-class (LeanProduction, n.d.). Most of the packaging lines of Heineken have a score of around 60%. An analysis for the composition of OPI-NONA for production line 52 is given in Chapter 3 System analysis.

OPI is a useful tool for the comparison between production systems since it is independent of the throughput of the system and only measures the efficiency of the system. Rødseth, Strandhagen, and Schjølberg (2015) mention that throughput is also a useful KPI for maintenance management in a manufacturing business. If the OEE increases the production line as a whole can make more products in the same time period because there are now fewer losses. This implies that the throughput rate also decreases. Measuring the throughput rate does not give more information.

As explained in Section 1.4, the design of a production line is of significant importance for the maintenance and investment cost of the production line (Battaïa & Dolgui, 2013). Heineken is mostly interested in finding the optimal production line design to reduce the effects of idling on the OPI-Nona. Heineken makes a distinction between short and long stoppages. Short stoppages are defined as a failure of a machine of which the time between the machine stop and the continuation of this machine took shorter than 5 minutes. Long stoppages are defined as stoppages in which this took longer than 5 minutes. The philosophy behind this distinction is that short stoppages are often uncomplicated to fix. It should be noted, however, that short stoppages occur frequently. While the direct downtime effect of the short stoppage does not affect productivity significantly, the idling problems that come with these downtimes do, since they are so frequent.

Besides the significant effect of idling on productivity levels, it also has another side effect. When a machine becomes idle, it suddenly has to stop producing, and when the breakdown has been relieved, it can start producing again. According to an operator, this stop and start of the machines caused more wear and tear than when the machines did not have to stop and start during production time. This increases the need for planned maintenance. Since long stoppages take by definition more than five minutes, the capacity of most of the buffers is not enough to overcome that one or machine becomes idle. For that reason, the choice has been made to only include the short stoppages in the simulation model. Since quality losses are a minor loss for productivity for production line 52 and the production line is a non-returnable line, the choice has been made to exclude quality losses out of the model. The production line's ability to deal with idling when a short stoppage has occurred can thus be calculated by dividing the production time by the operating time. This metric is abbreviated to OPI-OPT in this report and is the primary metric that is used as the performance indicator of the simulation model.

2.4 Idling

The concept of idling is explained in more detail in this section. First, the possible machine state and the abbreviations that are used to mention the positioning of machines is explained, which will be used from now on in the visualisations. Hereafter the concept of the two types of idling is explained in Section 2.4.2. Section 2.4.3 deals with the formulas that are used for the calculation of the failures of each machine. The time that a machine can still operate will another machine in the line has a failure is called buffer time and is discussed in Section 2.4.4. The next section deals with the time that is needed to recover the buffer to the nominal holding amount when a stoppage has occurred. The last section explains the current model that is applied at Heineken Zoeterwoude. This model is called the V-graph.

2.4.1 Machine states and abbreviations

In this section, the notations that are used to indicate specific parts of the production line is explained, which is based on the possible machine status according to MES, In figures, the buffers are abbreviated to B and the machines to M. To indicate which machine is mentioned the following notation is used which also hold for buffers:

- M_n/B_n = The relative position of the machine/buffer
- M_{n-k}/B_{n-k} = The machine/buffer that is k stations/buffers before machine n in the process
- M_{n+k}/B_{n+k} = The machine/buffer that is k stations/buffer after machine n in the process

The buffers are assumed to be always working for this bachelor thesis since breakdowns of the buffer occur very rarely. The machines are, however, able to be in six different:

- *Producing.* The machine is said to be producing when the material is being processed in the machine
- *Planned production stop.* The machine is in planned production stop when the machine is not producing because of a planned stop.
- *Starvation.* A machine is in starvation mode when the machine is not able to produce due to a shortage of material to produce.
- *Blockage.* A machine is blocked when the buffer after the machine has not enough capacity to put the finished materials and can therefore not produce.
- *Stoppage.* The machine has a breakdown if the machine is not able to produce due to an internal failure of the machine.
- *Unknown.* In a small number of cases, the machine is put into "unknown state" if the machine is not able to produce for an unknown reason. Most often of the times unknown means that the operator had to fix the machine while the machine was not registered to be in failure.

The planned stop machine state is not of interest for this research since this machine state does not influence the value of OPI-OPT by definition. It is mentioned since the machine can be in this state in real life, but this will not be modelled.

2.4.2 Blockage and starvation

As mentioned in Section 2.3, idling is an occurrence that can reduce the productivity levels of the equipment. The techniques that are laid out in Section 2.5 mostly focus on reducing the effects and occurrence of idling by implementing a different model for the production speed of the production line. Idling takes place when a machine is not able to produce because of a problem that originated somewhere else in the line. There are two types of idling which are the machine states blockage and starvation:

- Blockage means that the conveyor belt (the buffer) has reached its maximum capacity and the machine has no place for the produced goods.
- Starvation happens when the buffer in front of the machine has run out of items. The machine cannot receive any input anymore and is therefore not able to produce.

The concept of idling can better be explained by an example. In Figure 8, machine Mn is having a breakdown. However, the other machines can still operate since the buffers can provide the needed materials for some time after downtime for the other machines. The buffer capacity of a machine is directly correlated to the area of the line. The longer and broader the conveyor belt is, the more bottles can temporarily be stored before the next step in the line. The longer the breakdown lasts, the higher the chance that other machines are facing downtime because of idling problems. The more time it takes to get Mn working again, the fuller buffer Bn becomes, and the emptier buffer B_{n+1} and B_{n+2} become. If there is no WIP on B_{n+1} and B_{n+2}, machine M_{n+1} and M_{n+2} will become starved. If the conveyor belt Bn has reached its maximum capacity, M_{n-1} is not able to produce anymore since there is no place for the finished goods.

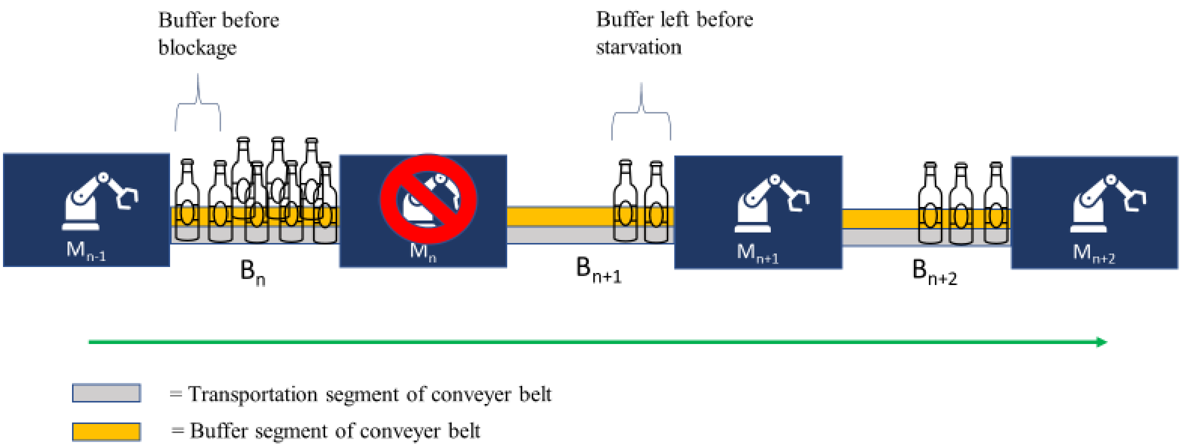


Figure 8: Blockage and starvation effect by breakdown machine

The production line is parallel for most of the production line. This helps to reduce the effects of idling. Suppose one of the parallel machines is facing downtime. In that case, the other identical machine can, in most cases increase its production speed slightly and take over some of the production of the other parallel machine.

2.4.3 Failure calculation

As explained in Section 2.2.1, breakdowns generally do not have a high impact on the productivity of the machine itself. However, they can diminish the productivity level significantly with the idling effect that can be caused by the breakdowns. This can be seen in the performance analysis.

There is a direct relationship between the reliability of a machine and the number of breakdowns that, on average, occur. The reliability of the machines in the production line varies significantly. In this section, the formula for the calculation for metrics that are related to failure and availability are given. This will be used to calculate the values and distributions for the up and downtime of the machines. There are three ways to estimate the rate of failure (Slack, Brandon-Jones, & Johnson, 2016, pp. 624-629). These are explained below.

- Failure rate: This metric shows the number of failures over the operating time. The failure rate can be calculated with the number of failures over the available production time.
- Reliability: The chances of a failure occurring. This is often expressed in Mean Time Before Failure. Most focus in this chapter will be on the reliability of the machines since that is also the way of working for Heineken Zoeterwoude.
- Availability: the amount of available useful operating time as explained in Section 2.2.2

Heineken mostly uses the failure rate or availability metric to show the rate of failures for each machine in MES. Since Heineken makes a distinction between short and long stoppages, the two metrics are shown both the short stoppages and long stoppages. Mean Time Before Failure (MTBF) expresses the amount of time it on average takes before a long stoppage has happened. On the contrary, Mean Time Between Assist (MTBA) denotes the average amount of time between two successive short stoppages. The formula used to calculate MTBF is provided in Formula 2, while calculation for MTBA is shown in Formula 3.

$$MTBF = \frac{operating\ hours}{Number\ of\ long\ stoppages} \tag{2}$$

$$MTBA = \frac{operating\ hours}{Number\ of\ short\ stoppages} \tag{3}$$

Another way to show the frequency of failures that is used by Heineken is based on availability. While operational availability shows the amount of operation time that a machine does not has a short stoppage, technical availability shows the amount of operation time that a machine does not has a long stoppage. The formula that is used by Heineken to calculate the frequency and time duration between downtime is:

$$Operational\ Availability = \frac{Production\ time}{Operating\ time} \tag{4}$$

$$Technical\ Availability = \frac{Operating\ time}{Actual\ production\ time} \tag{5}$$

The time that is needed to fix a short stoppage is called Mean Stoppage Time (MST), while the time that is needed to fix a long stoppage is called Mean Time To Repair (MTTR). MES registers the average time that is needed to fix for both types of stoppages under the corresponding name.

$$MTTR = \frac{Total\ time\ long\ stops}{Total\ number\ of\ long\ stops} \tag{6}$$

$$MST = \frac{Total\ time\ short\ stops}{Total\ number\ of\ short\ stops} \tag{7}$$

2.4.4 Buffer time

Stochastic production lines are subject to disruptions of machine failures and variations of production time by the machines. These disruptions can lead to idling and therefore, a decrease in throughput. The conveyor belts in between the machines act buffers that can help to reduce the effects of these disruptions and decrease the idle times of the machines. Buffers help to protect the machines that did not have a failure to have a lower chance to become starved or blocked and thus acts as a time buffer for the operators to repair the failed machine (Ameen et al., 2018).

Ameen et al. (2018) researched the effect of an increasing amount of buffer capacity of two identical parallel machines linked to the next machine via a buffer. They found that buffer capacity could increase the productivity of the line significantly if the buffer capacity increases from a small amount. However, after a specific buffer size is reached increasing the buffer size has a minimal effect on the throughput of the system.

The term buffer time is used in this report to indicate the amount of time that the buffer can prevent a machine from becoming idle when another machine in the line has faced failure. This buffer time depends on the buffer in between the machines and the production speed of the machines. Most of the machines can produce at a lower and some at a higher rate than the nominal speed. This speed regulation is done with sensors which measure the fill level of the buffers. When the buffer in front of the M_n is becoming starved, M_{n-1} may get a signal to reduce production speed and thereby increase the time before this machine gets blocked.

The conveyor belts of production line 52 have two functions: the transportation of parts and the buffer function. The transportation part of the buffer is the amount of buffer capacity that is needed on the conveyor belt for finished goods of one machine to move to the next machine. The buffer segment is the extra buffer capacity that can be used on a buffer. Heineken has adopted the philosophy that the bottleneck machine should have the highest priority in the line. Because of this reason, Heineken has applied the V-graph methodology, which is explained in more detail in Section 2.3.6. To protect the bottleneck as much as possible, Heineken tries to minimize the chance that the bottleneck machine becomes idle. The company attempts to achieve this by using the buffer in a specific way. In the optimal buffer state, the buffers in front of the bottleneck machine are entirely filled with WIP, while the downstream machines are as empty as possible while still providing constant WIP to the machines downstream. The ideal state of a buffer system is in Figure 8. Buffers downstream of the bottleneck are also called anti-block buffers and machines upstream of the bottleneck are also called anti-starve buffers.

As can be seen in Figure 9, a transition from a higher percentage of blockage of the machine to starvation happens at the bottleneck machine. The machines upstream of the bottleneck more often become idle because they cannot release their finished material. In contrast, the machine downstream of the bottleneck more often do have the required materials anymore for production when they become idle (Härte, 1997).

If machine M_{n+1} has a breakdown, then machine Mn can produce at its nominal speed till the buffer capacity of M_{n+1} has become full. If machine Mn-1 has a breakdown than Machine Mn can produce till al the WIP on buffer Bn has been gone through machine M_n. By trying to achieve the optimal buffer states, the buffer time of the bottleneck machine is at the maximum attainable level.

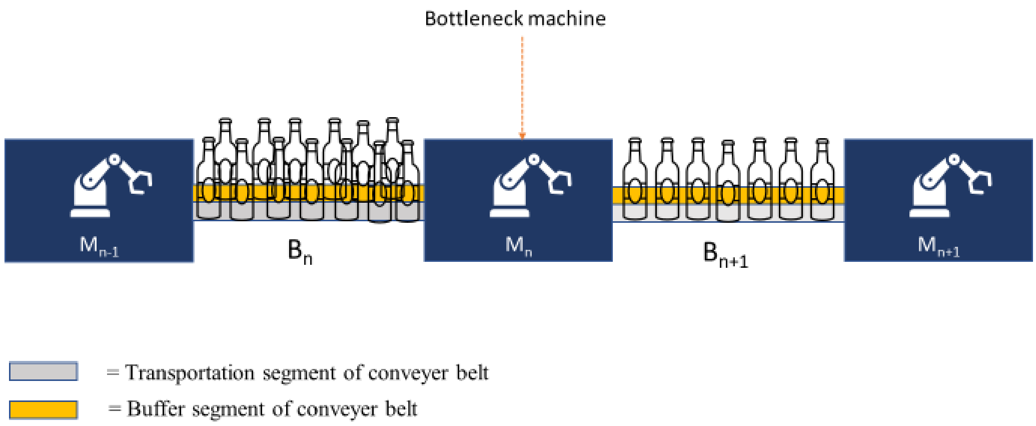


Figure 9: Visualisation of the optimal buffer usage

The formula for starvation and blockage differ slightly. Starvation happens when there is no material available anymore in front of a machine. For this reason, the remaining material amount in front of the machine and the speed of the machine is of importance. Contrary to blockage, the amount of remaining capacity after the machine and the production speed of the machine determines the time before the blockage occurs. The formula for buffer time before a blockage happens is given in Formula 8, while the formula for buffer time before starvation happens is given in Formula 9.

$$\text{Buffer time (blockage)} = \frac{\text{Capacity on } B_n}{\text{Production speed of } M_{n-1}} \tag{8}$$

$$\text{Buffer time(starvation)} = \frac{\text{Capacity on } B_{n+1}}{\text{Production speed of } M_{n+1}} \tag{9}$$

The buffer time is illustrated in Figure 9 for a production line that was not in the optimal state when the breakdown of M_n occurred. Please note that machine M_n is, in this case, is not the bottleneck machine, as shown in Figure 9. The production line may not be in the optimal state since it did not have enough time to return to the nominal fill rates after, e.g. a previous failure or a changeover. When the breakdown occurred at M_n, buffer B_n contained 700 products and buffer B_{n+1} had a buffer size of 800 products. In this case, the maximum buffer size of both the buffers is equal to 1200 products. If we assume the simple case that the processing speed of M_{n-1} and M_{n+1} is 50 parts per minute, the time for the starvation of M_{n+1} is 800/50 = 16 minutes, while the time till the blockage is (1200-700)/50 = 10 minutes. If M_n starts working again within 10 minutes of the failure, neither M_{n-1} and M_{n+1} become idle. If the time is longer than 10 minutes before the repair but shorter than 16 minutes, only M_{n-1} becomes blocked.

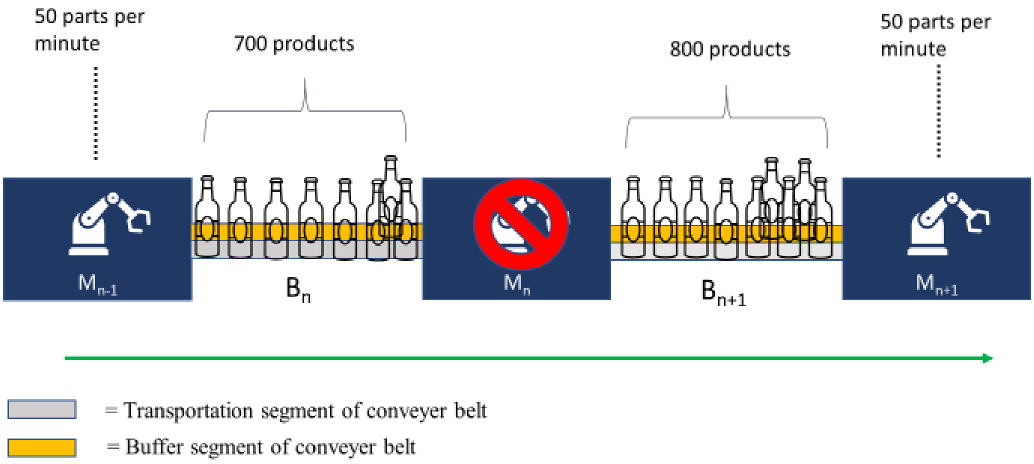


Figure 10: Buffer time calculation illustrated

2.4.5 Recovery time

As explained in Section 2.3.4, the buffering strategy used by Heineken is to have full buffers upstream of the bottleneck machine and an empty buffer segment for buffers downstream of the bottleneck machine. The recovery time is the time it takes before a buffer has a nominal level of inventory again after a stoppage or another buffer disrupting event (e.g. change-over or planned maintenance). The production line has sensors that measure the fill rate of the buffers. Based on this information, the machines can work faster or slower than is needed to increase the buffer time or when the breakdown has been lifted, to decrease the recovery time. The recovery time can be calculated by the difference between the number of products currently on the buffer and the nominal amount for the type of buffer (either full or empty) divided by the difference in processing speed of the next (anti-blockage buffer) or previous (anti-starvation buffer).

$$Recovery\ time_{anti-starve} = \frac{Maximum\ buffer\ level - current\ buffer\ level}{Difference\ production\ speed\ M_n\ and\ M_{n-1}} \quad (10)$$

$$Recovery\ time_{anti-block} = \frac{Current\ buffer\ level}{Difference\ production\ speed\ M_{n+1}\ and\ M_n} \quad (11)$$

2.4.6 V-graph

Heineken has implemented the v-graph methodology, that is also known as the bowl phenomenon to increase the performance of the production line. Frederick S Hillier (1966) was the first person that coined the idea of the bowl phenomenon. In his work, he found out that output rate could be improved in an unpaced asynchronous with unreliable exponential production times for four workstations by an implementation of the bowl phenomenon. The model assumes that a higher throughput could be achieved by assigning the lowest workload to the centre of the production line and an increasing workload towards the begin and end. Smunt and Perkins (1985) confirmed that this is the case for production lines with high variability. Considerable research works for different kind of production lines also found positive effects of the bowl phenomenon on the throughput rate of the production line (Rao, 1976).

Tom McNamara, Shaaban, and Hudson (2016), along with many other researchers, state that the bowl phenomenon might outperform balanced lines if the line features some sort of variation in processing time. The essential advantage over an evenly spread workload is that the first machine has a lower probability of becoming starved, and the last server has a lower probability of becoming blocked (Karwan & Philipoom, 1989). It should be noted, however, that there has been very little academic research on the bowl-phenomenon for multi-model lines, so these conclusions may not hold for production line 52.

The bowl phenomenon has gained many appraisals, but not everyone agrees with the validity of the research design. Rao (1976) found that in a production line of 3 machines with the first and last having exponential service times and the middle machine a constant distribution for service time, allocating an inverse distribution for work generated the best results. Not every production line can thus be optimized by unbalancing it in the same way. Baker (1992) explains that the bowl shape's performance has to do with the variability and the distribution of the service times of the machines of the production line. Smunt and Perkins (1985) argue that the bowl phenomenon is only superior to balanced production lines when the amount of variance is high enough. The bowl phenomenon is particularly useful if the used buffer model is not adequate, and the variation of processing time is high (Shaaban et al., 2014). The bowl phenomenon does, however, result in a high work-in-process which acts as a buffer for machines. El-Rayah (1979) found that in the right configuration, the bowl phenomenon outperforms an ascending, descending and the sawtooth allocation of workload for normal, lognormal and exponential production time distributions.

The bowl phenomenon is an application of the Theory Of Constraints (discussed in Section 2.5.1) methodology since it tries to elevate the constraint in the production line. A limitation of the bowl phenomenon is that it assumes that the bottleneck is fixed. As can be seen in the Bottleneck Analysis (Section 3.4), the current constraint in the line is not the machine with the lowest maximum production speed anymore. For that reason more flexible solutions than the current model will be evaluated during the experimentation of the simulation model.

For optimal use of the line, the effects of idling should be minimised as much as possible. The shorter it takes to repair a breakdown, the less idling will occur. Heineken should strive for an MST that is at least as low as the average buffer time. If a breakdown is relieved within the buffer time, idling does not occur. If a breakdown has occurred, the buffers need recovery time before the buffers are at their ideal levels again. The recovery time should best be as low as possible, and Heineken should strive for a recovery time below the average time between stops to reduce idling effects. The advised recovery times and MTTR are investigated in Chapter 3.

2.5 Improvement techniques

This thesis assignment focusses on finding improvements in the production line by finding the optimal unbalancing method. This section deals with possible ways of improving the production line in this way. First, the Theory Of Constraint is explained, which is used for the improvement of the bottleneck. The Drum Buffer Rope methodology is based on the TOC and also applied by Heineken. Section 2.5.3 deals with the detection of the bottleneck in the production line. The next two sections deal with workload allocation and buffer allocation, respectively. Section 2.5.6 presents the limitations of the research—lastly, Section 2.5.7 summaries Chapter 2 Theoretical perspective.

2.5.1 Theory of Constraints

The lean improvement methodology can be combined with the theory of constraints, which has been first described by Goldratt and Cox (1984) in the book The goal. The main objective of lean is the smooth progress of materials in the processes. The bottleneck in this process distorts this flow. The technique that solely focusses on improving the constraints of the system and thereby increasing the performance of the whole process is called Theory of Constraints (TOC) (Nigel Slack, 2016, pp. 521-522). The extent of the goal achievement is delimited by at least one constraint, which is the bottleneck of the process. The following theorem can prove this statement in the case the goal is to achieve a higher throughput: If there is nothing that would constrain the system to increase the throughput, the throughput rate of the system would be infinite. Therefore there is always a constraint. The theory declares that one hour lost at the bottleneck machine is one hour lost for the whole system.

Underutilization of the bottleneck severely affects the whole system. The bottleneck machine should, therefore, operate as much as possible. The following steps are executed to improve the performance of the system, according to TOC:

1. Identify the constraint of the system
2. Decide how to make the most use of the bottleneck. The cost of improvement should preferably be low.
3. Coordinate the system to the changes that are made to the bottleneck. It could be possible that the bottleneck has shifted to another component in the system. If the constraint has been disappeared, go to step 5.
4. Elevate the constraint. If it was not possible to exploit the bottleneck in step two and three, significant changes might be needed to eliminate the constraint and increase the performance of the system.
5. Go back to step 1.

The TOC is used to find the bottleneck of the process. The possible solutions are based on the TOC principle to increase the performance of the bottleneck. Section 2.5.3 deals with the way bottleneck can be detected.

2.5.2 Drum Buffer Rope

The Drum Buffer Rope (DBR) methodology is derived from TOC. This methodology describes where in the production system control should occur. Most production lines are not balanced in the capacity of the equipment over the line. This means that there is likely a bottleneck in the production line that has a lower capacity than the rest of the line. This bottleneck equipment is called the drum in DBR, which sets the beat for the production line. Because the capacity of the drum is the lowest of the line, the availability of the machine should be as high as possible. A buffer should be located in front of the machine to ensure higher availability. Communication is needed between the machines and drum to prevent the buffer capacity in front of the Drum gets full and blocked. This communication is called the rope. If machines in front of the machines are working faster than the bottleneck, this would only lead to an accumulation of products in front of the bottleneck machine. The system needs to be adjusted to the slowest machine of the line, and the largest buffer should be located in front of the bottleneck machine (Slack, Brandon-Jones, & Johnston, 2016, p. 341).

The effectiveness of DBR has been analysed by Thürer, Stevenson, Silva, and Qu (2017) in comparison with another improvement methodology called Workload Control release method for a general flow shop and pure flow shop with different amount of bottleneck intensity. They found that the DBR was superior in case of a high bottleneck severity. However, the workload control release method was performing better if there was not a big difference between the bottleneck capacity and the other machines.

DBR limits itself to one fixed constraint in the system. In real life, however, the constraint can move since outputs of the machines are stochastic (Lee, Chang, Tsai, & Li, 2010). It also only suggest adding a buffer in front of the drum to ensure high availability of products for the constraining machine but does not suggest adding a buffer after the buffer to prevent starvation.

2.5.3 Bottleneck detection

As explained in the Theory of Constraints method, there is always a constraint or bottleneck in a process. The first step in improvement, according to TOC, is finding the constraining factor in the system for the performance of the studied factor, which in this case, is the productivity of the line. In this section, the bottleneck machine is presented and is analysed further in Section 3.4. A bottleneck can either be detected analytically or via simulation. Two methods are used to find the bottleneck in the production line. These methods are turning-point methodology and Mean Effective Rate. These are explained in this section.

There is not a consensus in literature for the exact definition of what a bottleneck of a production process is. The choice has been made to define a bottleneck as “a machine or equipment whose performance impedes the overall system performance in the strongest manner” (Y. Li, Chang, Xiao, & Arinez, 2015). During this thesis assignment, we are mostly interested in the performance of the productivity of the line. This translates the definition of the bottleneck to: “the machine in the production line whose performance impedes the OPI-OPT in the strongest manner”. Two bottleneck analysis methods are explained. First, the Turning point methodology is explained. Hereafter the Mean Effective Rate is explained.

The turning point methodology proposed by L. Li, Chang, and Ni (2009) is a method that signals where the bottleneck occurs in the production line based on machine status. To be marked as the turning point in the production line, the machine has to fulfil two conditions: the transition from blockage being higher than starvation should happen at that machine and the total idle time should be lower than the surrounding machines of the turning point machine.

Another condition to be a turning point is that the total starvation plus blockage time of the bottleneck should be lower than the two neighbouring machines. This means that the total production time plus downtime is the highest percentage of effective working time. If the two conditions are met, then the bottleneck of the production line is the turning point defined by this methodology. In the case that no bottleneck can be found with the first protocol, the following theorem follows: if each machine’s blockage is higher than the starvation percentage, the first machine is the bottleneck. If the contrary is true, then the last machine is the bottleneck of the process (L. Li et al., 2009). Figure 11 shows how the bottleneck can be detected based on the blockage and starvation times. In the case of Figure 11, the bottleneck of the process according to the turning point methodology is machine M4, since this machine is the turning point of the machines being more starved than blocked and the total idle time is the lowest for this machine.

Figure 11: The turning point methodology (L. Li et al., 2009)

The Mean Effective Rate (MER) is another way to find the bottleneck in the production line proposed by Härte(1997). According to this methodology, the machine that has the lowest effective rate in the line is usually the bottleneck. Effective rate is the proportion of time the machine is producing based on the availability multiplied with the average production speed of this machine. The pasteuriser has the lowest production speed of the machines in the production line, but a high availability and therefore it has not the lowest MER score as can be seen in Section 3.4.2.

$$MER = \frac{production\ time}{production\ time + \text{failure time}} \times \text{production speed} \quad (12)$$

2.5.4 Workload allocation

As explained in Section 2.3.6, Heineken currently has adopted the V-graph methodology for production line 52, which describes how the workload should be assigned over the line. It has long been thought in the manufacturing industry that balancing a production line by allocating buffer capacity evenly over the line and setting the production speed equal for each machine would generate the best results. For a balanced production line, all the machines should have a production speed that is equal to each other. It may be possible that this is not possible since a machine is not able to produce at the same rate as the other machines can do in the line. An unbalanced line can provide the solution since an unbalanced production line problems do not seek to align a production line perfectly but instead seeks to find the optimal allocation of work and buffers for maximal productivity and throughput of the production line (Tom McNamara et al., 2016). In a few cases, a balanced production line gives the best results. This is not the case for an unpaced line, which is one of the properties of production line 52, as described in Section 2.2.2. This type of production line can never be truly balanced and will always face downtime (Thomas McNamara, Shaaban, & Hudson, 2013). Shaaban et al. (2014) investigated the literature of the bowl phenomenon in their work “fifty years of the bowl phenomenon”. They found that the bowl phenomenon is particularly useful when the buffer quantities are not adequate, and the fluctuations in the task times due to unexpected stops is high.

The extra workload capacity that can be given to machines in an unbalanced workload allocation line is often called protective capacity. Craighead et al. (2001) researched the relationship between protective capacity patterns and the throughput and bottleneck stiffness of a production line of 5 servers. The patterns that have been used by those researchers are also used to find the optimal workload allocation model in this study. The patterns that are considered during the simulation study are: inverse bowl, bowl, level, sawtooth and reverse sawtooth model. The patterns are visualised in Figure 12.

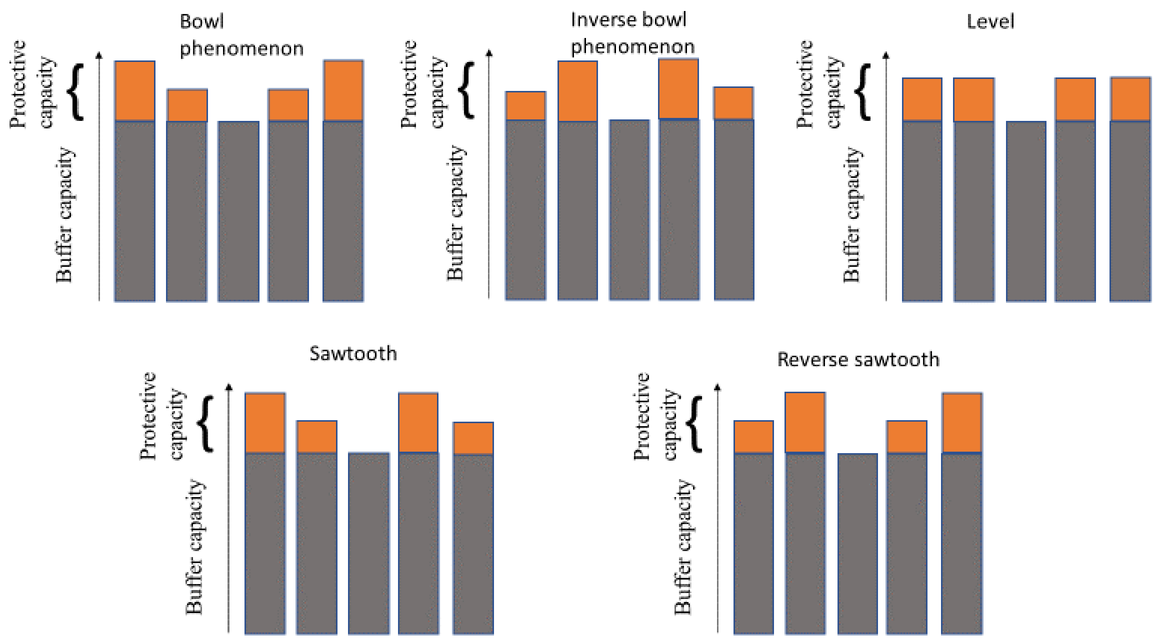


Figure 12: The workload allocation models

There are indications that the current v-graph model that is used by Heineken Zoeterwoude may not be optimal for production line 52. De Vries (2019) researched the main causes of losses in the productivity of this line before this thesis assignment. De Vries found that the current unbalancing method may not be optimal for production line 52. With the help of a simulation program, De Vries evaluated what the effect of different workload models was on the productivity of the production line. She found that the production line may perform better under a different workload allocation model. She proposed the implementation of the sawtooth model and to less extent the peak and constant model for an improved line performance. De Vries(2019) assumed that the pasteuriser is the bottleneck of the production line, which might not be the case based on the what definition for the bottleneck is given. Since the bottleneck of the process is not clearly defined and may be another machine in the production line than currently thought, more flexible solution will be used for the optimisation of the productivity of the line. These solutions will be based on the TOC methodology, together with the workload models in Figure 12.

2.5.5 Buffer allocation

Buffers are used to deal with the variance of the operation times of machines. They can increase the throughput of the production line by limiting the propagation of the distributions, but at the expense of additional investments, floor space and inventory costs (Amiri & Mohtashami, 2012). Buffer allocation is recognized by production line designers to improve the productivity and throughput of the system. A buffer capacity that is too high can increase the capital cost and indirect cost. At the same time, a buffer capacity that is too low will result in low utilization of the machines. A trade-off has to be made between those two factors in the available floor space (Kose & Kilincci, 2015). Frederick S. Hillier, So, and Boling (1993) found that for optimal performance, the buffer allocation should follow an inverse bowl phenomenon pattern by allocating more buffer space to the centre of the production line. The philosophy behind this pattern is the same as for the bowl phenomenon; it tries to reduce the chance of starvation and blocking for the first and last station, respectively.

Using buffers in an asynchronous production line may increase the reliability of the whole line since buffers can absorb problems that occur in case of idling. Increased reliability decreases the variability of the production line. Romero-Silva, Marsillac, Shaaban, and Hurtado-Hernández (2019) state that the more random variability the production process has, the less productive the process is. The allocation of buffer quantities and positioning along the production line may, therefore, be able to increase the productivity of the production.

Experiments concerning the buffer amount of the conveyor belt will be conducted to determine the effect of a varying amount of buffers in the production line. These experiments will also be based on the TOC principles and seek to elevate the constraint of the system by increasing the buffer allocation in the line.

2.5.6 Failure reduction

The productivity loss of the OPI-OPT metric consists entirely out of idling caused by short stoppages. Since the machines in the production line have different functions and are in different health, the failure patterns of the machines differ significantly. It is not known to what extent Heineken can decrease the number of failures, but the experiments for the failure reduction can show what the most critical machines are for Heineken to focus on failure reduction and should, therefore, be investigated.

2.6 Cost-benefit solutions

In this section, the possible cost and benefits of the solutions are laid down. Three types of possible solutions were presented in Section 2.5.4, 2.5.5 and 2.5.6, which are used together with TOC. Since the cost of adding more buffer capacity or increasing the production speed of the machines were not known beforehand, quotations were sent to the supplier for the proposed changes. At the moment of finishing this report, the only quotation received was for increasing the production speed of the pasteuriser to the maximum level. The cost of this implementation is X euros. The costs to increase the buffer amount in front of the machines or to increase the production speed of the other machines than the pasteuriser have been discussed with my supervisor Eric Kögeler.

The costs for the workload experiments are based on the costs for the software updates. A specialist of the production line supplier is able to change the processing speed of the machines by changing the settings of the machines. The cost of changing the speed of the machine by the specialist is estimated at X euros per machines. Increasing the buffer amount is estimated to cost X euros. The cost of failure reduction is not known. These failure experiments are conducted to show the possible profit that could be generated when the amount of failures or MST has decreased for the machines.

The profit of the experiments is based on the increase in the productivity of the line. An increase of 1% OPI-NONA results in a yearly increase of X euro profit (De Vries, 2019). Since the outcome of the results is based on the OPI-OPT metric and not the OPI-Nona metric, a calculation was made to translate the profit number to 1% OPI-OPT increase. The average value of the amount of production time left over from the effective working time due to productivity losses was 51,34% for the first half-year of 2020. An increase of 1% OPI-OPT, therefore, leads to an increase of around 0, 5134% in OPI-Nona. A 1% increase in OPI-OPT is therefor assumed to increase the profit of production line 52 by X per year.

2.7 Limitations research design

The primary purpose of the study is to increase the productivity of the production line by using TOC and together with an optimal allocation of workload and buffer. The study mainly focusses on how to improve the productivity of this particular production line. It may, however, be possible that the findings could also be used for other production lines that have the same properties.

This research mostly focusses on improving the productivity of the production line by decreasing the idling times of the machines caused by short stoppages and thereby increase the productivity of the system. Other factors that could increase the value of OPI-Nona are not studied during this research because they are not included in the scope of the research.

Another limitation of the research is that it is based on the performance of production line 52 in the first half-year of 2020. When improvements or changes are made to the system, the optimal solution of this research may not work in the same way as intended anymore. Some machine was not included in the scope of this research since too little data was available about those.

2.8 Summary theoretical perspective

Section 2.1 showed the outline of the production and the most important properties of production line 52 that were used as a starting point for the theoretical framework. The management paradigm TPM was explained to get a better understanding of the improvement culture of Heineken Zoeterwoude. The KPI OPI-OPT has been selected as the measurement of productivity to compare solutions based on the TPM methodology. This KPI indicates the percentage of time that is lost due to minor stoppages and the idling that are caused by them.

Furthermore, the effects of idling on the production line are explained, and the solution that has been applied by Heineken to reduce these effects is also described. Possible solutions for productivity increase are mostly based on decreasing the occurrence of idling. This choice has been made since idling is a significant restricting factor in the productivity of the line.

The workload allocation model is used together with TOC to find solutions that increase the productivity of the line. Also, experiments are run with regards to an increase of buffer amount to understand the behaviour of the line better. Lastly, this report will advise on the most critical failures to be fixed to increase the productivity of the line. The possible solutions design and expected effects are depicted in Figure 13 below. Since the correlation between optimal buffer allocation and workload allocation is tight, an optimal combination of both is tried to be found. The possible improvements are indicated in orange, while the solutions are constraint by a factor shown at its left side. The most important KPI in the study is the productivity of the line, which is shown on the right side in green in the picture. Since the cost for the increase in productivity should be earned back within X years of implementation, the KPI cost is also of importance.

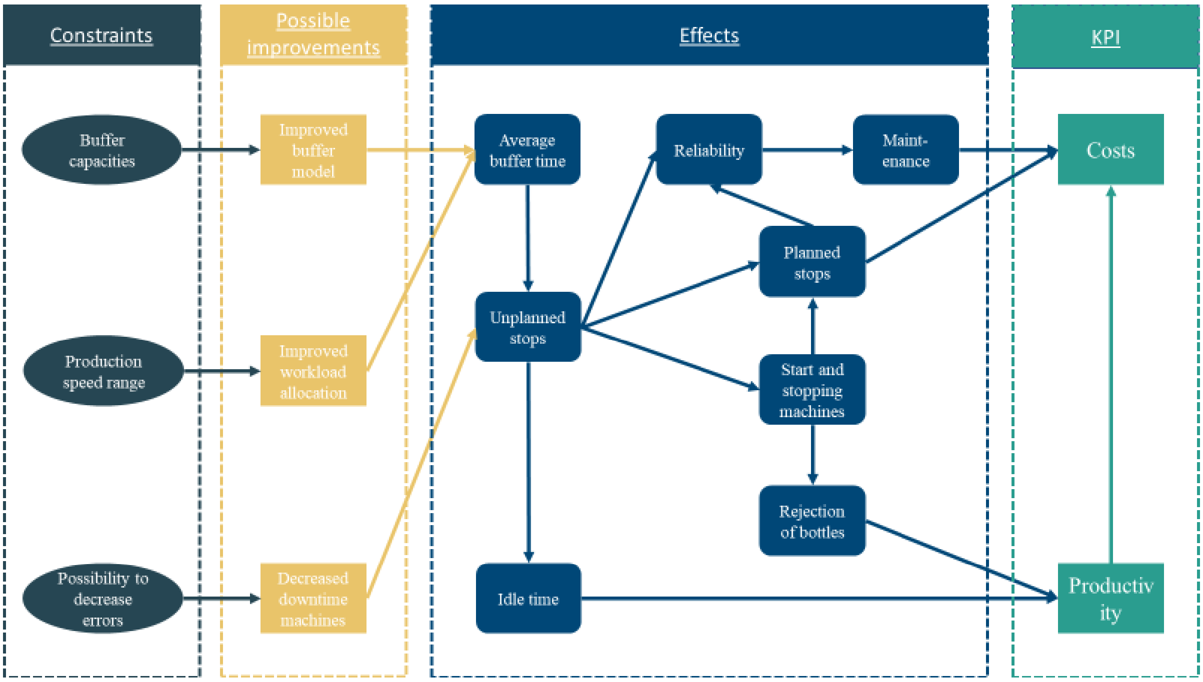


Figure 13: Summary of Chapter 2

3

Current system analysis

This chapter deals with the analysis of production line 52 to derive the input for the simulation model, the validation of the simulation model and to get more insight into the working of the production line. First, the data collection method that is used by Heineken is explained, which is one of the data sources for the analysis of the system. Section 3.2 deals with the productivity performance of production line 52. Section 3.3 analyses the machine speeds, buffer properties and the failure behaviour. Section 3.4 analyses the bottleneck of the system with the methods that were described in Section 2.5.3. Lastly, Section 3.5 describes which experiments are used for the simulation model. These are based on the system analysis and the possible solutions as described in Section 2.5.

3.1 Data collection method

According to Robinson (2006, pp. 119-153), three types of data exist. These are available data, retrievable data and data that cannot be retrieved in any way. This unretrievable data can be estimated or retrieved via sensitivity analysis, or the data can be seen as an experimental factor. It was not possible to retrieve all the data that was needed. This data was then calculated based on the estimation of the operators of the line.

Most of the information that is used during the system analysis comes from the Manufacturing Execution System (MES). This is a tool that either automatically or manual registers relevant data for Heineken. The software that controls the production line and also automatically registers information for MES is called Programmable Logic Controller (PLC). Machine breakdowns are mentioned as PLC errors in MES, and therefore the same terminology is used. A PLC error is thus equivalent to a breakdown of a machine.

The application MES reporting is a tool that can analyze raw data from MES with pre-set parameters and gives the most important information or summary of the data. These parameters differ by analysis, but most often include the timeframe and the machine on which the user wants the analysis to be done. The choice has been made together with the supervisor of Heineken to analyse the production line for the first half-year of 2020. This time frame should be recent enough to give relevant information of the line while the timeframe should be long enough to even out the outlying results. The data is relevant for only the 250ml type of bottle since this the data was able to be retrieved for this bottle type.

3.2 OPI-OPT performance

The same methodology as in Section 2.2.1 is used to understand what the losses of production line 52 are for productivity. The OPI-OPT performance is calculated by dividing the production time by the operating time. Since the way the production line is programmed, idling is registered as a short stoppage even though a long stoppage before that depleted most of the buffer in front of the machine. Therefore, the OPI-OPT is calculated by looking at the results of the week with the least amount of short failures in 2020. This occurred in week 29 in which the value of OPI-OPT turned out to be 81,01%. This is used for validation of the simulation result of the current model later.

3.3 Input parameter analysis

This section explains the way the input parameters are obtained and presents the results of the analysis. The input parameters for the simulation model are production speed, maximum possible production speed, buffer amount, buffer times and for the failure modelling the metrics Mean Stoppage Time, Technical Availability, Operational Availability and Mean Time To Repair are used.

3.3.1 Production speed

The production speed of the machines in the production line follows the v-graph methodology. This processing speed is, however, not always constant and depends on the fill levels of the buffers. Line sensors can measure the fill level of buffers of the line. The machine varies its processing speed based on the information it receives from the line sensors. The exact way the machine speed is programmed is not known by the operators or anyone whom I had spoken to do. This programming was done by the supplier of the machines and could not be retrieved by Heineken itself. For that reason, the nominal production speed has been investigated, which is the production speed set to run under most conditions.

For some machines, the nominal production speed could be retrieved from their control panel, and for the other machines, the production speed was retrieved from estimates from operators. The nominal speed of the machines is based on the v-graph principle, as explained in Section 2.3.6. Figure 14 shows the production speed of the machines that are modelled in the simulation.

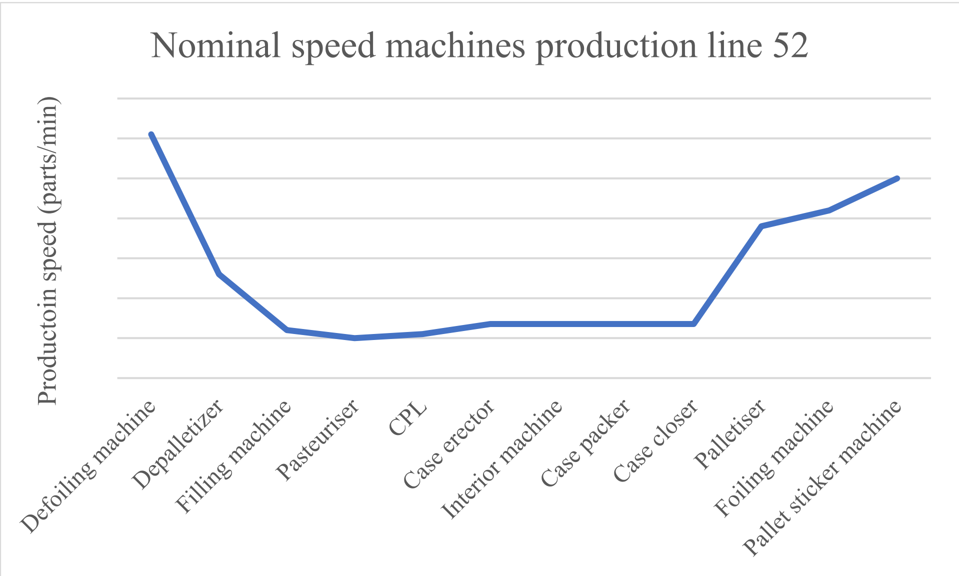


Figure 14: Production speed of the machines of production line 52

Note that v-graph does not hold for the case packer and the interior machine, and there is no increase or decrease of production speed at those machines. Although these machines are relevant for the rest of the line, they are not interconnected, and therefore the speed of these machines are all set equal to the case packer. The shape of the v-graph can be seen in the graph above, but the step of increase is not fixed over the line.

3.3.2 Maximum possible production speed

The current production capacity of the machines in Figure 14 is not the maximum speed that can be attained by the machines. The supplier initially calculated the current workload capacity of the line as the best workload allocation model. The exact effects of increasing the production speed of the machines are not well known, only to what extent the production speed can be increased. The maximum was retrieved from the line description document of the supplier. The maximum possible speed per machine is shown in Table 1. The experiments, as described in Section 3.5, take the maximum possible speed into account.

Table 1: Maximum possible speed for the machines

Machine	Subtype	Max speed
Defoiling machine	520	
Depalletizer	520	
Filling machine	521	
	522	
Pasteuriser	520	
CPL	521	
	522	
Case erector	521	
	522	
Interior machine	521	
	522	
Case packer	521	
	522	
Case closer	521	
	522	
Palletiser	521	
	522	
Foiling machine	520	
Pallet sticker machine	520	

3.3.3 Buffer amount

The buffer amount is defined for this thesis assignment as the highest number of WIP that a buffer can attain. With the help of the counters in the control panel of the machines, this number can be evaluated. The following method was used to retrieve the buffer amount: almost every Monday the production line has to start up because weekly repairs, cleaning and changeovers are needed. This is called a stop day. During this process of starting up, each machine is set to run after each other with enough time in between to cause a blockage on the next buffer. The counters of the machines were set to zero before the machine was turned on. Each machine was then able to operate until a blockage has occurred because the next station in line was not turned on. When the blockage has happened for the machine, the maximum buffer amount of the buffers in front of the machine is equal to the new counter amount. This number gives information about the number of products on the buffer but not the different parts of the line. Not all conveyor belt are straight lines from one machine to the other, but some converge or diverge to give more flexibility to the line. This principle was explained in Section 1.2.1. A split in a line is denoted as split, and the place where two lines join together is named converge. Most of the buffers are for that reason split up in smaller buffer parts for this analysis. An estimation based on the advice of operators was used for the ratio of buffer amount per buffer part between the machines. The buffer amount for all the relevant parts of the line is shown in Table 2 below.

Table 2: The amount of buffer for the relevant parts of the line

From	To	Amount
Defoiling machine	Depalletiser	
Depalletiser	Split	
Split	Filler 521	
Split	Filler 522	
Depalletiser	Filler	
Filler 521	Converge	
Filler 522	Converge	
Split	Pasteuriser	
Filling	Pasteuriser	
Pasteuriser	Pasteuriser	
Pasteuriser	Split	
Split	CPL1	
Split	CPL2	
Pasteuriser	CPL	
CPL1	Converge	
CPL2	Converge	
Join	Split	
Split	Case Packer 1	
Split	Case Packer 2	
CPL	Case Packer	
Case erector 1	Interior placer 1	
Case erector 2	Interior placer 2	
interior placer 1	Case packer 1	
interior placer 2	Case packer 2	
Case erector	Case Packer	
Case packer 1	Case closer 1	
Case packer 2	Case closer 2	
Case packer	Case closer	
Casecloser 1	Join	
Case Closer 2	Join	
Join	Palletiser 1	
Join	Palletiser 2	
Case closer	Palletiser	

Palletiser	Foiling machine
Foiling machine	Pallet labeller

The buffers are grouped per machine in Table 2. The last line of each buffer group has a border around it and shows the total amount of buffer from one station to the next station and is the sum of the buffer segments of the buffer group.

3.3.4 Buffer times

The speed of the buffers determines the minimum time that is needed for WIP to go from one machine to the other. This speed is tuned to never be a restricting factor in the productivity of the line by moving the WIP as least as fast as the machine in front of the buffer is producing. The buffer time, as shown in Table 3, is the time that is needed to move from one machine to the other when the line is empty. To obtain the buffer times, a bottle was marked with red tape and placed on the line when it was completely empty and the time was registered by stopwatch several times.

Table 3: The buffer times of the parts of the buffers.

From	To	Buffer time
Defoiling machine	Depalletiser	
Depalletiser	Split	
Split	Filler 521	
Split	Filler 522	
Depalletiser	Filler	
Filler 521	split	
Filler 522	split	
Split	Pasteuriser	
Filling	Pasteuriser	
Pasteuriser	Pasteuriser	
Pasteuriser	Split	
Split	CPL1	
Split	CPL2	
Pasteuriser	CPL	
CPL1	Join	
CPL2	Join	
Join	Split	
Split	Case Packer 1	
Split	Case Packer 2	
CPL	Case Packer	
Case erector 1	Interior placer 1	
Case erector 2	Interior placer 2	
interior placer 1	Case packer 1	
interior placer 2	Case packer 2	
Case erector	Case Packer	

Case packer 1	Case closer 1
Case packer 2	Case closer 2
Case packer	Case closer
Casecloser 1	Join
Case Closer 2	Join
Join	Palletiser 1
Join	Palletiser 2
Case closer	Palletiser
Palletiser	Foiling machine
Foiling machine	Pallet labeller

3.3.5 Failure statistics

The choice has been made to model the failures based on the availability and the time to repair for each machine. Since the long failures are not included in the scope of this research, only the operational availability of the machine is shown in Table 4. These failures are based on the availability of the machine and the time to repair the failure. Both the MST as the operational availability was retrieved from MES reporting. Plant simulation uses the negative exponential distribution for calculation of MST.

Table 4: The operational availability and MST for short stoppages

Machine	Subtype	Operational Availability	MST (s)
Defoiling machine	520		
Depalletizer	520		
Filling machine	521		
	522		
Pasteuriser	520		
CPL	521		
	522		
Case erector	521		
	522		
Interior machine	521		
	522		
Case packer	521		
	522		
Case closer	521		
	522		
Palletiser	521		
	522		
Foiling machine	520		
Pallet sticker machine	520		

3.4 Bottleneck detection

In this section, the bottleneck detection methods, as described in Section 2.5.3, are used to find the bottleneck machine of the process. First, the turning point methodology is applied in Section 3.4.1. The Mean Effective Rate is used for the bottleneck analysis in Section 3.4.2. Lastly, Section 3.4.3 analysis the amount of time that the possible bottlenecks were in a machine state.

3.4.1 Turning point methodology

The blockage and starvation times for each machine was retrieved from MES reporting to conduct the turning point methodology for the first half-year of 2020. Based on the turning point methodology, the labelling machine is the bottleneck machine of the process. The starvation time is higher than the blockage time from this machine on. Also, the total idle time is lower than the previous and next machine in the line.

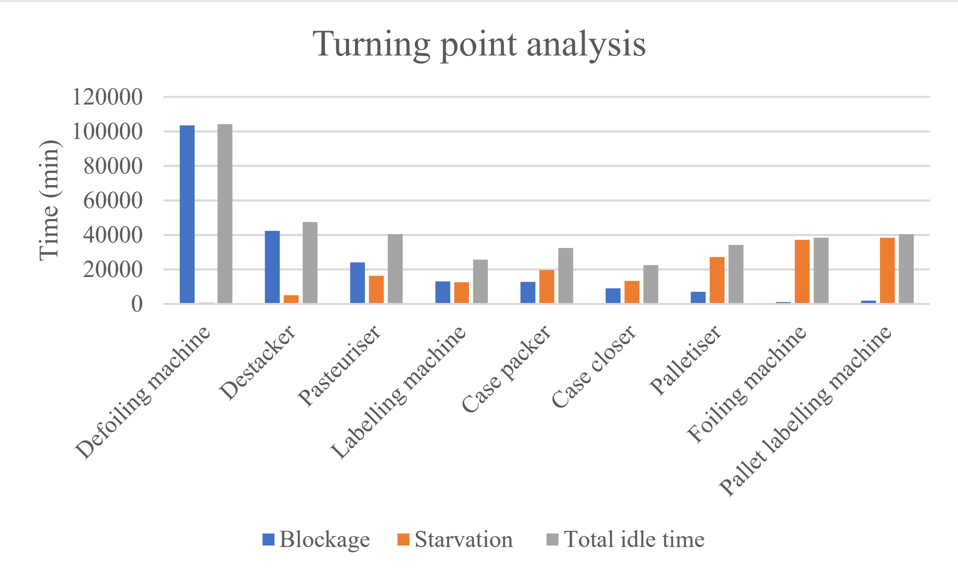


Figure 15: Turning point-based methodology for bottleneck detection

3.4.2 Mean Effective Rate

The Mean Effective Rate is another way to determine the bottleneck in the process. The machine with the lowest MER value is considered to be the bottleneck of the process. The machine with the lowest MER value is Case packer 2 with a value of X, but if the averages are taken of the stations, the CPL machines have a slightly lower MER value than the case packers. Table 5 shows the MER values and nominal processing speed of the machines of the production line.

Table 5: The MER compared to the nominal production speed

Machine	Subtype	Production speed	MER
Defoiling machine	520		
Depalletizer	520		
Filling machine	521		
	522		
Pasteuriser	520		
CPL	521		
	522		
Case erector	521		
	522		
Interior machine	521		

	522
Case packer	521
	522
Case closer	521
	522
Palletiser	521
	522
Foiling machine	520
Pallet sticker machine	520

3.4.3 Possible bottlenecks machine status

This section analyzes the machine status of the bottleneck machines. The CPL and the case packer came out to be the possible bottleneck of production line 52. Since the pasteuriser is assumed to be the bottleneck of the process and has the lowest current nominal production process, this machine is also analysed on its machine status.

The time on the y-axis in Figure 16 shows the amount of total time in minutes that a machine is a particular state. The machines are most often in the production state and are the highest for the pasteuriser since the amount of long and short stoppage are so low for this machine. The blockage time is the highest for the pasteuriser while the starvation time is the highest for the case packer, which is in line with the turning-point methodology.

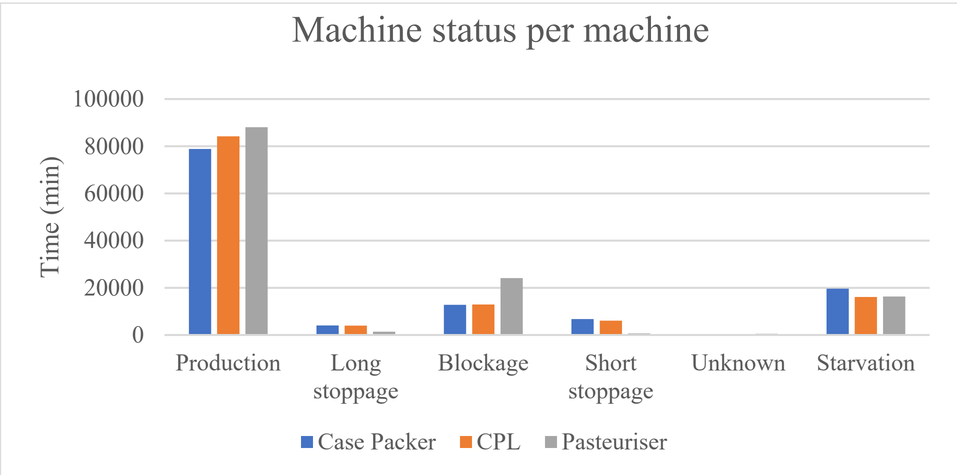


Figure 16: Time in machine state for the bottleneck machines in the first half of 2020

3.4.4 Conclusion bottleneck analysis

The results of the bottleneck analysis were remarkable since the machine with the lowest processing speed did not come out to be the bottleneck machine for the first half-year of 2020. Heineken has put much work to reduce the failures of the pasteuriser and to decrease the starvation time of the pasteuriser. Heineken has used the v-graph to increase the performance of the bottleneck machine and thereby the performance of the whole production line. The v-graph is focussed on increasing the performance of the bottleneck machine. This may have led to such an improvement in the performance of the pasteuriser that it is not the limiting factor of the production line anymore. It may be possible that the bottleneck of the production line has shifted over time since the focus for improvement was mostly centred around the pasteuriser. According to the TOC methodology, the bottleneck should be identified again if the bottleneck machine has shifted over time. The experiments in the next section will take into account the different possible bottlenecks from the bottleneck analysis.

3.5 Conclusion Chapter 3

Chapter 3 analysed the input parameters for the conceptual model and the possible bottlenecks of the line. First, the data collection method was explained, which was used for the capturing of the data. Most of the data were retrieved from MES or manual testing. It is calculated that idling and breakdown reduce productivity significantly. The value of OPI-OPT is calculated on an average value of 81,01% for the first half of 2020.

Next, the input data for the simulation was discussed. The following input data was shown: buffer sizes, buffer speed, machine speed, maximum possible speed, MST and availability of the machines. Lastly, the bottleneck of the production line was tested. Two different techniques were used, which showed varying results for the bottleneck of the line. Since the TOC method is applied, the improvement strategies are based on the possible bottlenecks found in Section 3.5.

4

Simulation set up

This chapter revolves around the conceptual model, the experimental set-up and the validation of the model. First, the conceptual model is explained. Next, the steps of simulation are explained, and the conceptual model is discussed. Hereafter the experimental set-up is discussed for the simulation model. Section 4.3 deals with the techniques that are used for validation and verification are presented. The simulation model is presented in Section 4.4. The experiments that are used to find improvements for the production line are shown in Section 4.5. Lastly, Section 4.6 summarises Chapter 4.

4.1 Conceptual model

There are several ways to describe a conceptual model. The choice has been made to describe the inputs and output, the assumptions and the simplifications for the conceptual model. Since the simulation is made in a DES, the simulation only calculates when an event happens and what the effect is of this event on the system. A logic flow has been made to understand better what events can occur and what the effects are on the system. These are included in Appendix F.

The process of simulation consists of four steps (Robinson, 2006). The first step is making the conceptual model. The conceptual model is a representation of concepts that help understand how the simulation works and what it is trying to model. Simplifications and assumptions should be taken at this stage. This has to do with the high impact of the conceptual model on the course of the simulation. The next step is to transform the conceptual model into a computational simulation model.

According to Robinson (2006, p. 99), the steps of the simulation are an iterative process, since the modeller may learn more things along the way which may give the need to go back in the simulation process and bring some changes. The author also notes that it is essential that the modeller takes an active approach to understand the problem better. For this research, close contact with the supervisor of Heineken is kept during the research and interviews with operators are conducted to understand the working of production line 52 well.

4.1.1 In and outputs of the conceptual model

Information with regards to the characteristics of the machines is needed to calculate the state changes over time. A distinction can be made between two main types of objects. These are the machines and the conveyor belt. First, the input for the machines are listed and then the buffer inputs.

Input machines

- *Processing speed*: The production speed of the machines is set according to the V-graph strategy. This is explained in Section 2.3.6. The processing speed of the machines is flexible, meaning that the production speed can be lowered and increased to a certain degree when this is required. For most machines, the average speed is taken, since this is the speed that was known for most of the machines.

- *MST*: This is the time between two short stoppages. This time can differ strongly between the machines since the function, and the health of the machine differs.
- *Operational Availability*: The percentage of time that a machine does not have a short stoppage.

Input buffers

- *Buffer amount of the conveyors*: This is the maximum amount of Work In Process that can be placed on the conveyor in front of the machine.
- *Buffer times*: The minimum time that is needed to move from one machine to the next. Most often WIP will take longer to move from one machine to the next machine because of accumulation effects. This is taken into account in the simulation model

The output of the simulation model is the metric OPI-OPT. The choice for this metric is explained in Section 2.5.1. Since only short stoppages are included in the simulation model, the throughput of the machines is based on the operation time. The value of OPI-OPT is calculated by dividing the throughput of the bottleneck machine by the maximum possible throughput that could be attained by the bottleneck machine.

4.1.2 Simplifications and assumptions

It is not possible to perfectly imitate the production process for computational complexity and time constraints. For that reason, some assumptions and simplifications are taken. Simplifications and assumptions are different concepts. Simplifications are used for faster simulation runs, help to increase transparency and speed up the implementation of the conceptual model. Assumptions, however, are made when there are uncertainties of the system modelled. The effect of the assumptions is taken into account during the discussion of the results. The assumptions are based on the work of van der Zee (2019), Robinson (2006, pp. 96-116), whom both gave guidelines for the assumptions of simulation and de Vries (2019, pp. 32-33). These assumptions and simplifications have been discussed with the supervisor of Heineken.

Simplifications:

- Unlimited supply and storage. We assume that there is an unlimited supply of pallets with empty bottles and storage for the pallets at the end of the line. This means that the first machine can never be starved and that the last machine is always able to release the pallets. In reality, problems may occur with the deliveries or the input of the production line or with the transportation of the pallets. This should be taken into account in the evaluation.
- Perfect external lines. Although it sometimes happens that, e.g., there is a problem with the supply of beer to the filler, this kind of events happen rarely and do not decrease the productivity levels significantly (see Section 3.2). Since the scope of the research is only on the internal parts of the production line, and this kind of events happen seldom and do not significantly decrease the productivity level of the line, this simplification decision has been made.
- Rejection of bottles. A small percentage of bottles are rejected because the product did not meet the minimum quality requirements. Bottles can be rejected at every stage if, for example, the bottle broke down because it crashed with another bottle. Since the percentage of rejected bottles compared to OPI-Nona is only 0,3%, it is not considered in this analysis.
- No breakdown buffers. It could be possible that a buffer has a failure, e.g., the motor is not working anymore. This happens rarely and is therefore seen as an infrequent event.

- The arrival rate is always sufficient. It is difficult to get accurate information about the arrival rate of pallets since this is done manually and not registered in MES. The operators always make sure that there are enough pallets for the first machine of the line, and this is thus not a constraining factor. We assume, therefore, that the buffer of the defoiling machine is always full.
- Bottles amount is reduced. Only one bottle is simulated for each box instead of the actual 24 bottles per box to speed up the simulation. This choice has been made in discussion with a simulation line expert who works for Heineken

Assumptions

- The fixed pace of conveyor belt. We assume that the speed of the conveyor belt is constant and does not fluctuate. The speed of the conveyor belt is always higher than the adjacent machines to ensure that the belt is not a constraining factor.
- Chosen time period is accurate. As explained in Section 2.5.6, the choice has been made to analyse the performance history for the first half-year of 2020.
- Nominal processing speed. The assumption is made that by not taking the fluctuations of processing speed into account for most machines that the simulation still accurately behaves like the real system. This assumption has been made since there it was challenging to get insight into this information.
- Failure pattern is constant. Since only the failures are known for the system in its current settings, no information is available for what the effects are of increasing the speed of the machines on the amount and duration of the failures. For that reason, the assumption is made that the failure pattern does not change by an increased or decreased speed level of the machine.

4.1.3 Summary conceptual model

The logic flow is described in Appendix F. In Figure 17, the rest of the conceptual model is explained. This model describes the most important input and output parameters and the simplifications and assumptions that have been taken.

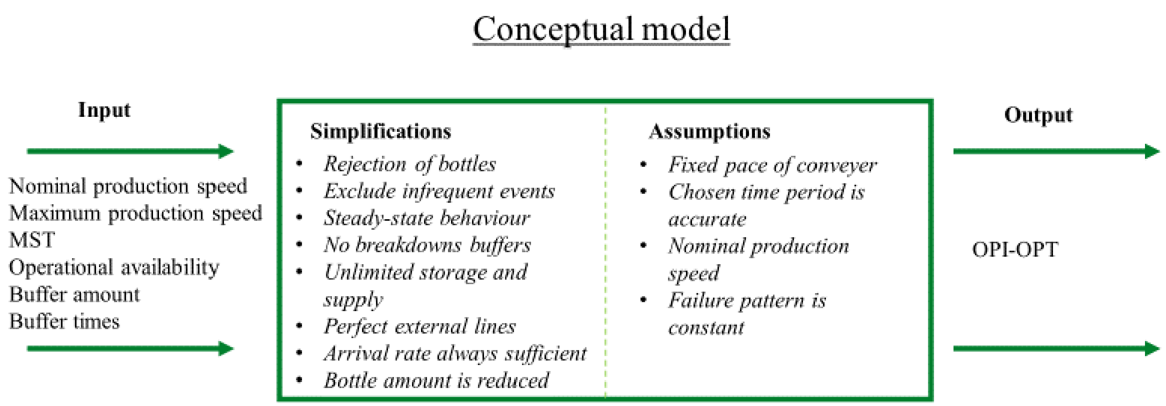


Figure 17: The conceptual model

4.2 Experimental set-up of the simulation study

Section 4.2 is concerned with the experimental set-up of the simulation study. First, the nature of the model is determined, which influences on the warmup period that is discussed in section 4.2.2. Lastly, the replication amount of the simulation is investigated in Section 4.2.3.

4.2.1 Nature of the model

The first step for the experimental set-up of a simulation study is to determine the nature of the model. Two types of simulation models exist: terminating and non-terminating. While the terminating model has a natural endpoint, the non-terminating model does not have this. These two models can be further split up into four possible subtypes although some subtype typically occurs more in either terminating or non-terminating type of model. The four distinct types are (Robinson, 2006, pp. 168-172):

- Transient output model. In this kind of model, the output fluctuates over time and does settle around the average of the output. This model is most often seen for terminating models
- Steady-state model. Non-terminating models often first have a transient output, but as time progresses, it approaches a steady-state performance. This transient output is the time that the system needs to warm up and is therefore called the warmup period or initialization bias.
- Steady-state cycle. In a steady-state cycle, the output never becomes steady-state, and the output in the cycles follow the same pattern.
- Shifting state cycle. Steady-state shift over time due to, e.g. a different product input.

Although the real model behaves like a shifting state cycle since different packaging material is used over time, the choice has been made to model the simulation as a steady-state model since only 250 ml bottles are modelled.

4.2.2 Initialization bias

The time before the simulations portraits steady-state behaviour is called the warm-up period. Since we are mostly interested in the steady-state behaviour of the system, this initialization bias should be removed. Since this warmup period can be noisy, it is better to take the average throughput of several runs and base the warmup period based on this. The warm-up period can be defined as the period of transient behaviour before steady-state behaviour. This means that the trend is neither going up or down but is rather fluctuating around the average steady-state throughput. It is important that the run length of the simulation is long enough for the simulation to transit to a steady-state form. There are several methods to determine the initialization bias, but the most commonly exact method is the Mean Squared Error Rule (MSER). The formula for MSER is given in Formula 13 below:

$$MSER\ (d) = \frac{1}{(m-d)^2} \sum_{i=d+1}^{m} (Y_i - \bar{Y}(m,d)^2) \quad (13)$$

d = purposed warm-up period

m = amount of observations in the plotted time series of output

$\bar{Y}(m,d)$ = average value for Yd+1 to Ym

The best warmup period is d such that the value of MSER(d) is minimal with d < m-5. The run length of the simulation should be at least ten times the warmup period to increase the efficiency of the simulation set-up. It may be possible that the best warmup period for the simulation changes the input data of other experiments are used. The warmup period is determined using a simulation run of ten hours for the bowl model that has been implemented by Heineken.

The observation value for the initialization bias is OPI-OPT since this is the output metric of the simulation. I have chosen a 5-minute interval for the capturing of the OPI-OPT for the initialization bias. In Figure 18, the result of the throughput of pasteuriser over time can be seen. The pasteuriser is the fourth station of the production line, and time is needed before the first parts arrive at this machine. The warm-up period is 14 time units which is equal to 70 minutes. The data is collected for the calculation of the OPI-OPT is from 70 minutes onwards in the simulation.

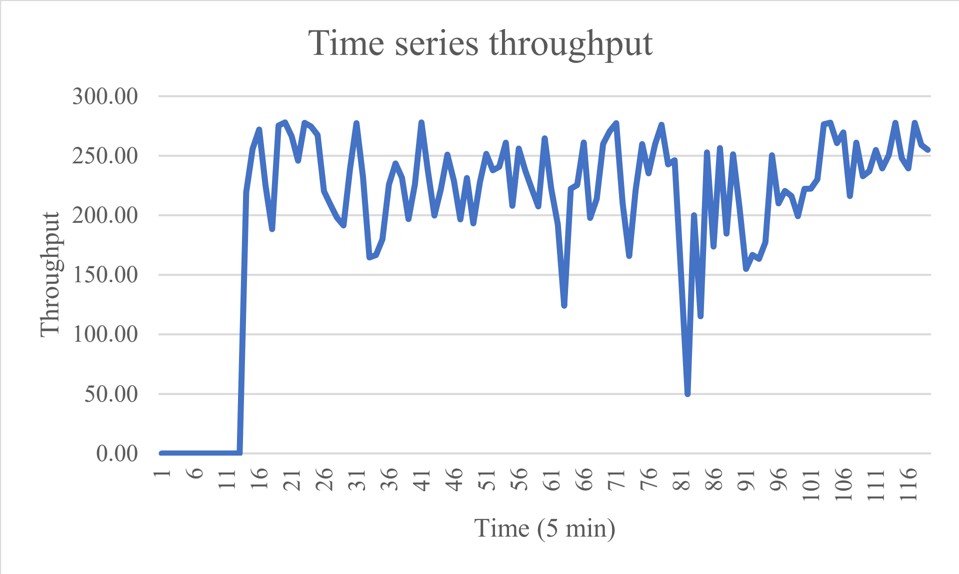


Figure 18: Time series for throughput

4.2.3 Replications amount

There exist several methods for the number of replications for each solution design. Law and McComas (1991, pp. 47-52) suggest that at least 3 to 5 replications are performed. For a more statistical method, the confidence interval (CI) method can be used. The more replications for the simulation are run, the smaller the confidence interval becomes in general. If the CI is sufficiently small compared to the average output of the replications, the amount of replications is sufficient. The CI compared to the average output is called the error. The formula to calculate the error is given in Formula 14.

$$d = \frac{t_{n-1,\alpha/2}\sqrt{S^2/n}}{|\bar{X}|} \tag{14}$$

$\bar{X}$ = average value output simulation

$t_{n-1,\alpha/2}$ = Outcome of t-distribution with n-1 degree of freedom and significance level of $\alpha/2$

S = Standard deviation of simulation output.

n = replication number

The choice has been made to set the number of replications for an error of < 0.01. The simulation run length was set to ten times the warm-up period plus the warm-up period (12 hours and 50 minutes), and several replications for an experiment were run. The outcome of the confidence interval after each new run are shown in Figure 19.

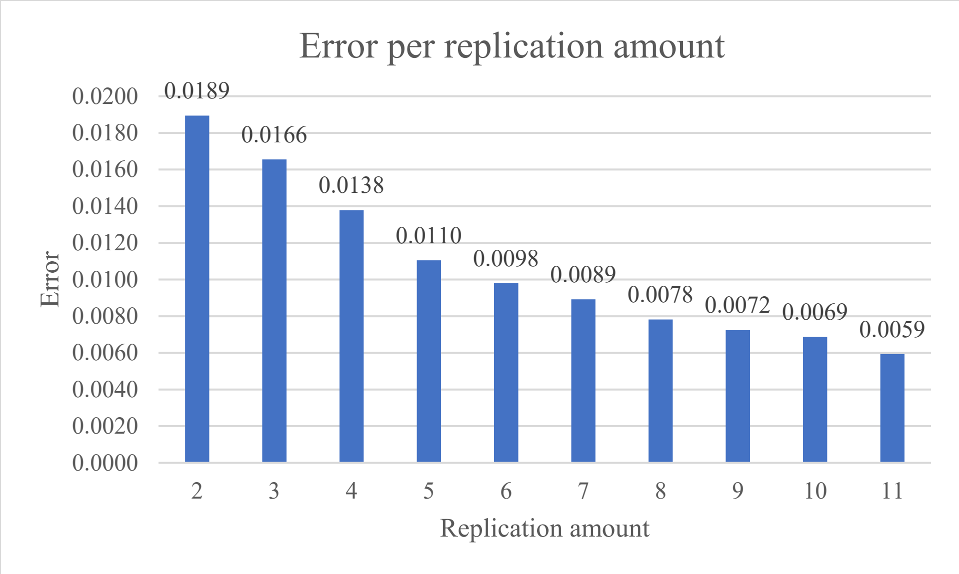


Figure 19: Error replications

As can be seen in Figure 19, the error decreases when the number of experiments increases. The choice has been made to conduct six replications for each experiment to achieve an error that is around 1% for each experiment.

4.3 Verification and validation

This section compasses the approaches to verify and validate the simulation study and the possible threats to these two. Verification in simulation studies is the process of checking that the simulation model accurately represents the real-world system. Validation is the accuracy of the purpose of the study. Verification and validation is a continuous process in the simulation study, since new information may arise over time which may be needed to implement in the simulation design.

4.3.1 Verification

Three types of verification are shown which are used during the simulation study to verify the model that has been made:

- Checking the code: It is essential that accurate data and code is used for the simulation. If the wrong logic or information is put into the system, the simulation could run significantly different than in the real world.
- Visual checks: Since the software that is used is a VIS simulation program, visual checks can be done to ensure that the simulation is running accordingly. By checking and predicting what happens from event to event, unexpected wrong behaviour can be filtered out of the simulation. The model should be evaluated by an expert of the line to ensure that the simulation is behaving naturally.
- Inspecting output reports. The performance of the simulation and the real-world data can be checked to validate if the same output is achieved.

4.3.2 Blackbox validation

Blackbox validation is a validation technique that is used when the model is considered done. This technique compares the output of the simulation with the real world output in a similar setting. When the difference in output is not significant, the model is said to have succeeded in the black box validation.

The simulation model has been validated on two points. The same input values as the real system are used for this validation. The validation points are the time of the WIP in the system and the OPI-OPT value.

First, the model has been validated by the productivity comparison between the simulation model and the real system. As described in Section 3.2, the value of the real value of OPI-OPT for Heineken is around 81,01%. As can be seen in Chapter five, the average value of OPI-OPT for the simulation of the production line was 81,00%. The values are very close to each other, and the output of the simulation model is thereby validated.

Secondly, the model has been tested if the time for a product to move from the beginning of the production line to the end corresponds with reality. According to an operator, the time that a bottle is in the system of production line 52 is at minimum one and a half hours when on failure occur. The first output of the last machine of the production line is produced between 1:25:00 and 1:30:00 with no failures in the simulation model when the production line has been started. This thus corresponds to reality.

4.4 Simulation model

The simulation model is based on the conceptual model and the data that has been found in Chapter 3. This section explains the general structure of the simulation model. The simulation model consists of several frames which help to keep an overview of the process and calculations of the model. The control panel is used as the navigation and summary of all the frames. The control panel is shown in Figure 19.

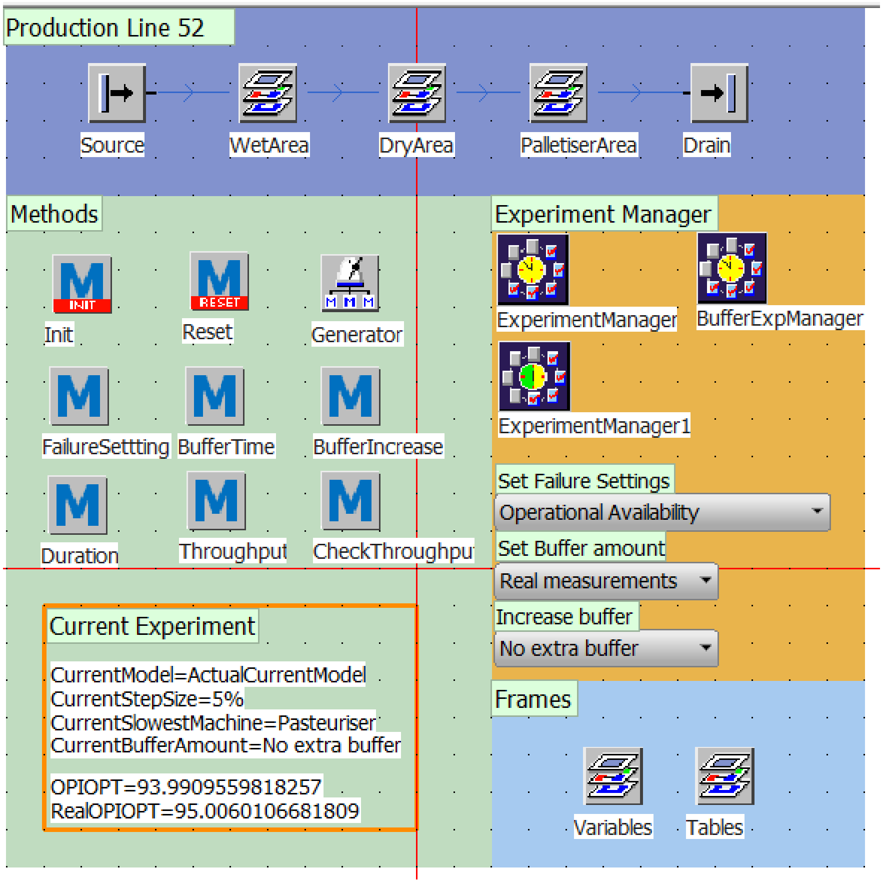


Figure 19: The control panel of the simulation model

The control panel is divided into five areas which all have their own function. The dark blue area shows the three parts of the production line. The methods in the green area are used to add logic to the simulation model and are used for the calculations. The experiment managers in the orange area are used to conduct the experiments in the simulation model. ExperimentManager can be used to conduct the workload model experiments, BufferExpManger is used for the experiments for the optimal buffer sizes. Lastly, experimentManager1 conducts the experiments with regards to failure and MST reduction.

The Variables frame in the blue area is used for the counters for the calculations, while the Tables frame contain the data for the experiments. The counters in the green section with the orange border show the experiment that is currently running. The OPIOPT counter shows what the value of OPI-OPT approximately should be when the input data of production line 52 is used. RealOPIOPT shows the output of the OPI-OPT KPI during the simulation of the experiment.

Lastly, the production line itself is modelled in the dark blue area. I have made the choice to divide the production line up in three parts to keep a better overview of the processes of the production line. The three parts are wet area, dry area and the palletizing area. The source generates the pallets with bottles, while the finished pallets exit at the drain. The pallets with empty bottles generated in the source are pushed to the first part of the wet area. Only the machines are described in Section 2.2.1 are included in the simulation model. Figure 20 Show the dry area of the simulation model.

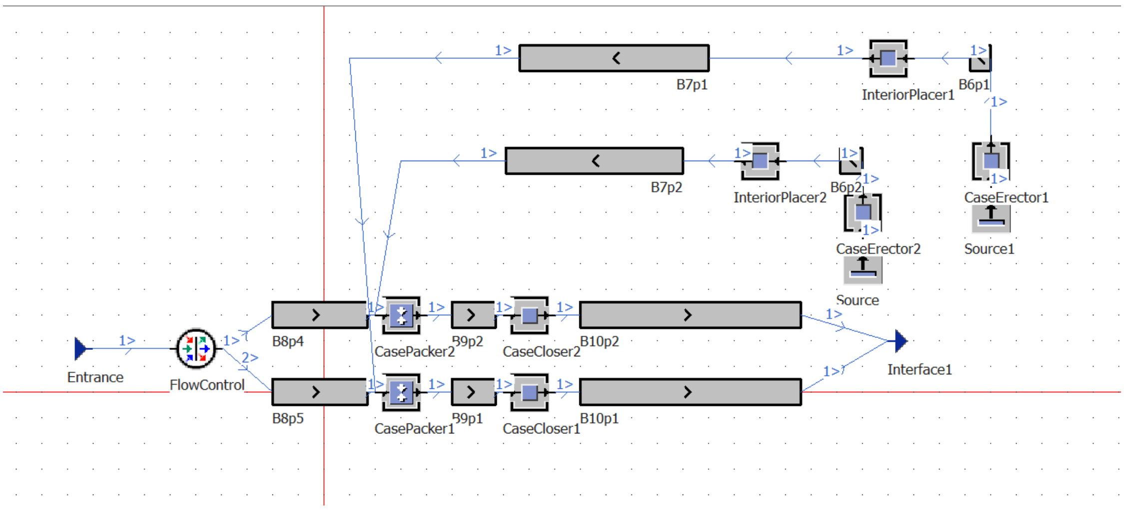


Figure 20: Visualisation of the simulation model of the dry area of production line 52

The dry area is the second part of the production line. This part of the production line contains the box lanes, the case packers and the case closers. Each machine has a processing speed based on the input data of the experiment. The failures are generated for each machine based on the availability, and the MST described in Section 3.3.5. These values are altered in experiments for the failure and MST reduction. The machines in the simulation model are connected with line segments. The input data that are used for these buffers are the buffer sizes and the buffer speed.

4.5 Experiments

This section elaborates the choice for the experiments for the simulation model to increase the productivity of the line. These are based on the TOC principle and Section 2.5.4 and 2.5.5. Three types of experiments are conducted: workload model, buffer and failure reduction experiments. The percentages in the table indicate the percentual increase in the experiments. Each percentage indicate a separate experiment.

Since the bottleneck of the production line may not be the pasteuriser, the workload models are applied for the possible bottlenecks of the system: the pasteuriser, CPL machines and the case packers. The models are based on an increased step size for processing speed per machine and are constraint by the maximum possible speed for each machine. The stepsize increase works in the following way: the stepsize increase is based on the speed of the bottleneck machine. If the bottleneck machine has a capacity of 100.000 bottles per hour, then the step increase is 5000. If the machine is not able to achieve the new proposed workload speed, the maximum possible speed of the machine is taken. The exact input for each workload model experiment can be found in Appendix A, B, C, D and E.

Table 7: Experiments for workload models for possible bottlenecks

Workload model	Bottleneck Pasteuriser	Bottleneck CPL	Bottleneck Case packer
Peak	5%, 10%, 15%	5%, 10%, 15%	5%, 10%, 15%
Bowl	5%, 10%, 15%	5%, 10%, 15%	5%, 10%, 15%
Levelled	5%, 10%, 15%	5%, 10%, 15%	5%, 10%, 15%
Sawtooth	5%, 10%, 15%	5%, 10%, 15%	5%, 10%, 15%
Reverse Sawtooth	5%, 10%, 15%	5%, 10%, 15%	5%, 10%, 15%
No protective capacity	5%, 10%, 15%	5%, 10%, 15%	5%, 10%, 15%

The best scoring workload allocation models from Table 7 are used for the experiments with buffer increase. First, the effects of a buffer increase for each machine are checked. The increase in buffers that are used is 10%, 20% and 30%. This is shown in Table 8.

Table 8: The experiments for an increased buffer amount for each machine

Workload model	Buffer increase
Peak	10%, 20%, 30%
Bowl	10%, 20%, 30%
Levelled	10%, 20%, 30%
Sawtooth	10%, 20%, 30%
Reverse Sawtooth	10%, 20%, 30%
Current model Heineken	10%, 20%, 30%

Since the overall buffer increase may be costly and difficult to implement also buffer experiments in front of the possible bottleneck machines are conducted. The same step increase as for the experiments in Table 8 is used for the specific buffer increase experiments in Table 9.

Table 9: Buffer experiments for buffer increase for possible bottleneck machines

Workload model	Extra buffer in front of pasteuriser	Extra buffer in front of CPL	Extra buffer in front of Case packer
Peak	10%, 20%, 30%	10%, 20%, 30%	10%, 20%, 30%
Bowl	10%, 20%, 30%	10%, 20%, 30%	10%, 20%, 30%
Levelled	10%, 20%, 30%	10%, 20%, 30%	10%, 20%, 30%
Sawtooth	10%, 20%, 30%	10%, 20%, 30%	10%, 20%, 30%
Reverse Sawtooth	10%, 20%, 30%	10%, 20%, 30%	10%, 20%, 30%

Current model Heineken	10%, 20%, 30%	10%, 20%, 30%		10%, 20%, 30%

Lastly, experiments that test the effect of a reduction of the number of failures or MST for the machines are evaluated. For each machine, an experiment is conducted that test the effect on productivity with a 25%, 50% and 75% decrease in MST and also for a 25, 50% and 75% increase in the operational availability. The failure experiments are shown in Table 10.

Table 10: Table with the experiments for reduction of MST and number of failures

Machine	MST reduction	Number of failure reduction
Defoiling machine	25, 50%, 75%	25, 50%, 75%
Depalletizer	25, 50%, 75%	25, 50%, 75%
Filling machine	25, 50%, 75%	25, 50%, 75%
Pasteuriser	25, 50%, 75%	25, 50%, 75%
CPL	25, 50%, 75%	25, 50%, 75%
Case erector	25, 50%, 75%	25, 50%, 75%
Interior machine	25, 50%, 75%	25, 50%, 75%
Case packer	25, 50%, 75%	25, 50%, 75%
Case closer	25, 50%, 75%	25, 50%, 75%
Palletiser	25, 50%, 75%	25, 50%, 75%
Foiling machine	25, 50%, 75%	25, 50%, 75%
Pallet sticker machine	25, 50%, 75%	25, 50%, 75%

4.6 Summary Chapter 4

This chapter presented the conceptual model, simulation model and the experiments. The conceptual model is summarised in Figure 17 based on the inputs, outputs, assumptions and simplifications. Also, a logical flow has been made, which is used in the simulation model to add logic. The warm-up period and replication amount have been determined in Section 4.2. The warmup period is set to 70, while six replications are conducted for each experiment.

Section 4.3 dealt with the verification and validation of the model. Three types of verification were explained, which were used during the modelling of the simulation model. The simulation model has been validated based on the number of failures generated and the value of OPI-OPT. The simulation model was presented in Section 4.4, with a description of how the model was made. Last, the experiments were presented in 4.5. The following experiments were presented: workload model, an increased buffer in front of all machines, an increased buffer in front of selected machines, reduced MST and increased availability of the machines.

5

Results experiments

In this section, the results of the experiments with the simulation model are discussed. First, the experiments of the different workload models are discussed. The best settings for each workload model are used for further analysis in Section 5.2 until 5.4. Section 5.2 evaluates the effects of an increasing buffer amount on the performance of OPI-OPT. Section 5.3 shows the results of an increase in buffer amount in front of the pasteuriser, CPL machines and the case packers. Section 5.4 analyses the effect of reduction of MST and failure amount for each machine. Section 5.5 summarizes the findings of Chapter 5.

5.1 Experiments workload models

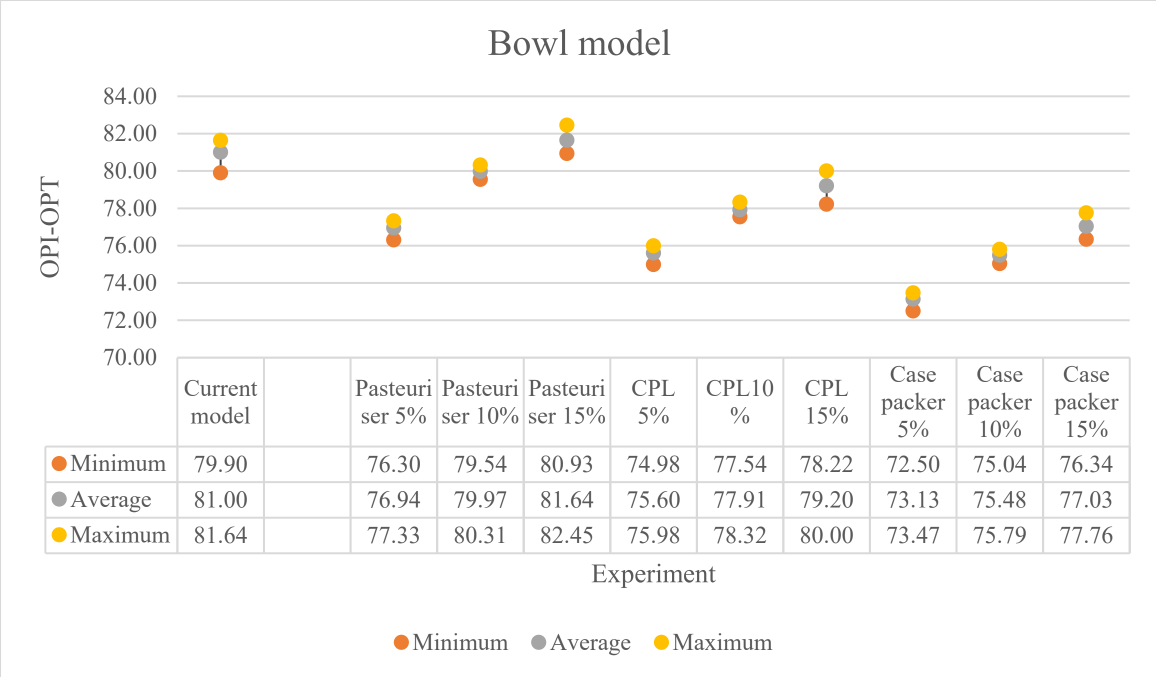
The simulation was run for the experiments for the workload models as described in Section 4.5. The current model that is used by Heineken is shown in each figure in Chapter 5 to highlight the differences between the value of the current model and the experiments. The results of the five models are described in the following order: bowl model, peak model, sawtooth model, reverse sawtooth model and lastly the levelled model. The minimum and maximum values from the six replications for each experiment are indicated for each experiment, together with the average value of the experiments.

For each workload model, nine experiments are conducted. The first experiment uses the current workload model that is used for production line 52. The next sequential experiments are based on the bowl, peak model, sawtooth model, reverse sawtooth model and the levelled model. Also, an experiment with a balanced workload model (that is every machine has the same processing speed) is conducted and shown in Section 5.1.6 to compare the results of an unbalanced and balanced model.

The first three experiments for each workload model are based on the pasteuriser as the bottleneck machine, the next three on the CPL and the last three experiments assume the case packers to be the bottleneck of the production line. Within these three experiments for each bottleneck machine, the first experiment uses a 5% step increase, the second a 10% step increase and the third a 15% step increase.

5.1.1 Bowl model

Heineken currently uses the bowl model to determine the workload of the machines for production line 52. The results of the nine experiments based on step size increase and bottleneck machine are shown in Figure 21. As can be seen in the figure, the experiments based on the pasteuriser as the bottleneck of the line resulted in the highest OPI-OPT. Since the experiment that takes the pasteuriser as the bottleneck with a step increase of 15% proved to be the best performing bowl model for production line, this experiment has been selected for further optimization in Section 5.2 and 5.3.

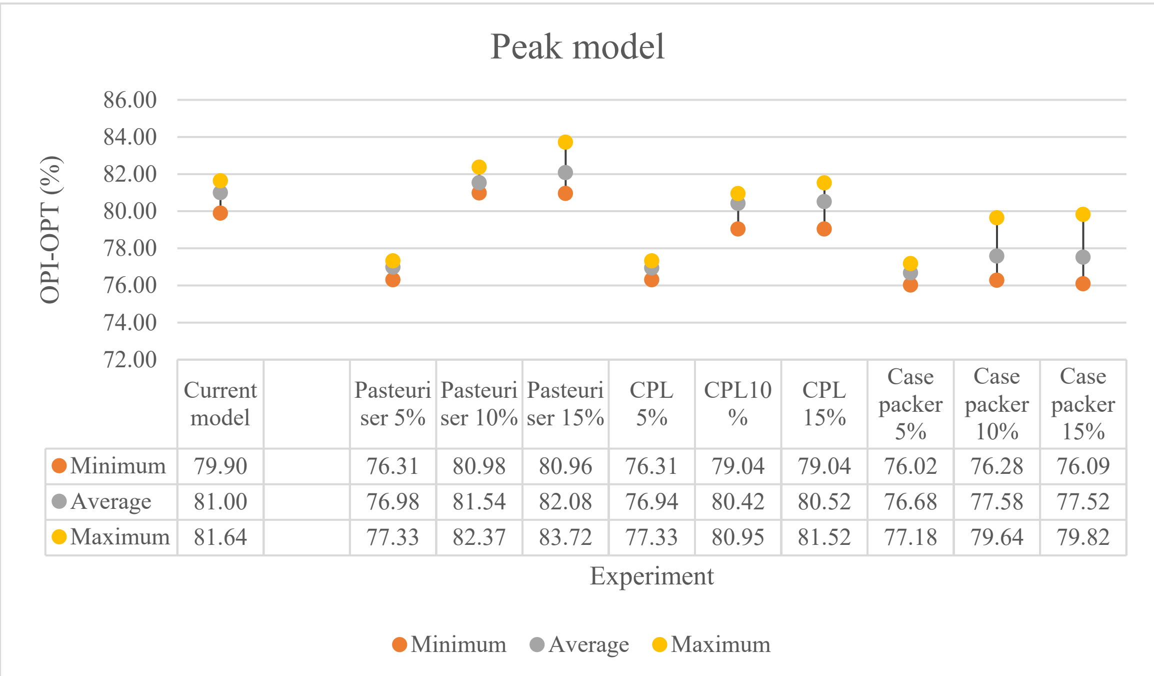


	Current model		Pasteuriser 5%	Pasteuriser 10%	Pasteuriser 15%	CPL 5%	CPL10 %	CPL 15%	Case packer 5%	Case packer 10%	Case packer 15%
Minimum	79.90		76.30	79.54	80.93	74.98	77.54	78.22	72.50	75.04	76.34
Average	81.00		76.94	79.97	81.64	75.60	77.91	79.20	73.13	75.48	77.03
Maximum	81.64		77.33	80.31	82.45	75.98	78.32	80.00	73.47	75.79	77.76

Figure 21: Results bowl model

5.1.2 Peak model

The same pattern as for the bowl model can be seen in Figure 22: the models based on the pasteuriser perform on average better than the models based on the CPL or case packers as bottleneck machine. The higher the step increase and thus, the higher the machine speed of the non-bottleneck machines (within the capacities of the system), the better the models are performing. Especially the step from 5% to 10% gives relatively much improvement in comparison with the step from 10% to 15%. The best performing experiment is the peak model with the pasteuriser as the bottleneck machine and step increase of 15%. This model will be further refined based on the optimal buffer amount and failure reductions in, respectively Section 5.2 and 5.3.

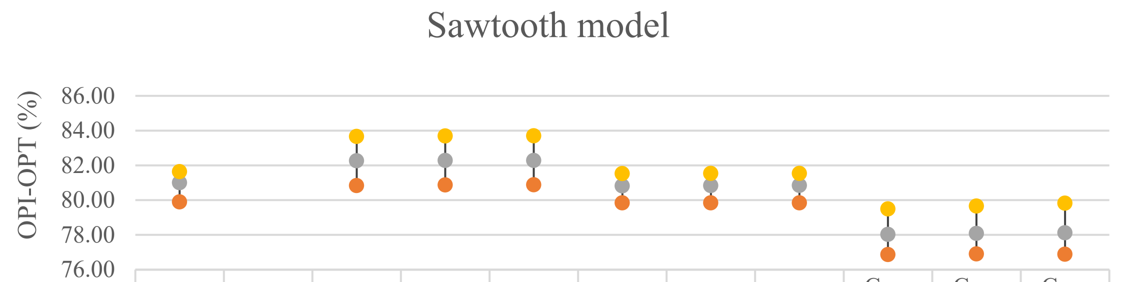


	Current model		Pasteuriser 5%	Pasteuriser 10%	Pasteuriser 15%	CPL 5%	CPL10 %	CPL 15%	Case packer 5%	Case packer 10%	Case packer 15%
Minimum	79.90		76.31	80.98	80.96	76.31	79.04	79.04	76.02	76.28	76.09
Average	81.00		76.98	81.54	82.08	76.94	80.42	80.52	76.68	77.58	77.52
Maximum	81.64		77.33	82.37	83.72	77.33	80.95	81.52	77.18	79.64	79.82

Figure 22: Results peak model

5.1.3 Sawtooth model

The experiment which takes the pasteuriser as the bottleneck resulted in the highest OPI-OPT value for the sawtooth model. The differences between 5%, 10% and 15% are minor, but the experiment that has the pasteuriser as the bottleneck and takes steps of 15% increase, showed the highest OPI-OPT with an average value of 82,28.

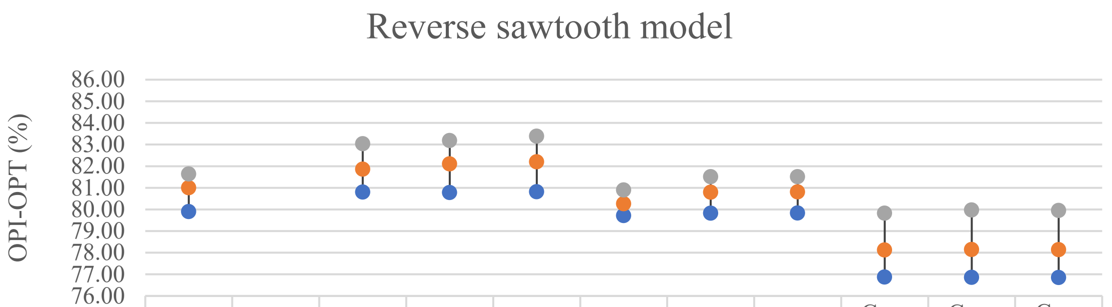


	Current model		Pasteuri ser 5%	Pasteuri ser 10%	Pasteuri ser 15%	CPL 5%	CPL10 %	CPL 15%	Case packer 5%	Case packer 10%	Case packer 15%
Minimum	79.90		80.84	80.88	80.88	79.84	79.84	79.84	76.87	76.90	76.89
Average	81.00		82.26	82.28	82.28	80.82	80.84	80.84	78.03	78.08	78.12
Maximum	81.64		83.67	83.69	83.70	81.52	81.54	81.54	79.50	79.66	79.82

Figure 23: Results sawtooth model

5.1.4 Reverse sawtooth model

As can be seen in Figure 24, the best performing models are based on the pasteuriser as the bottleneck machine. The differences between the model experiment for the pasteuriser bottleneck are again small, but the best performing experiment is 15% step increase with an average value of 82,20.

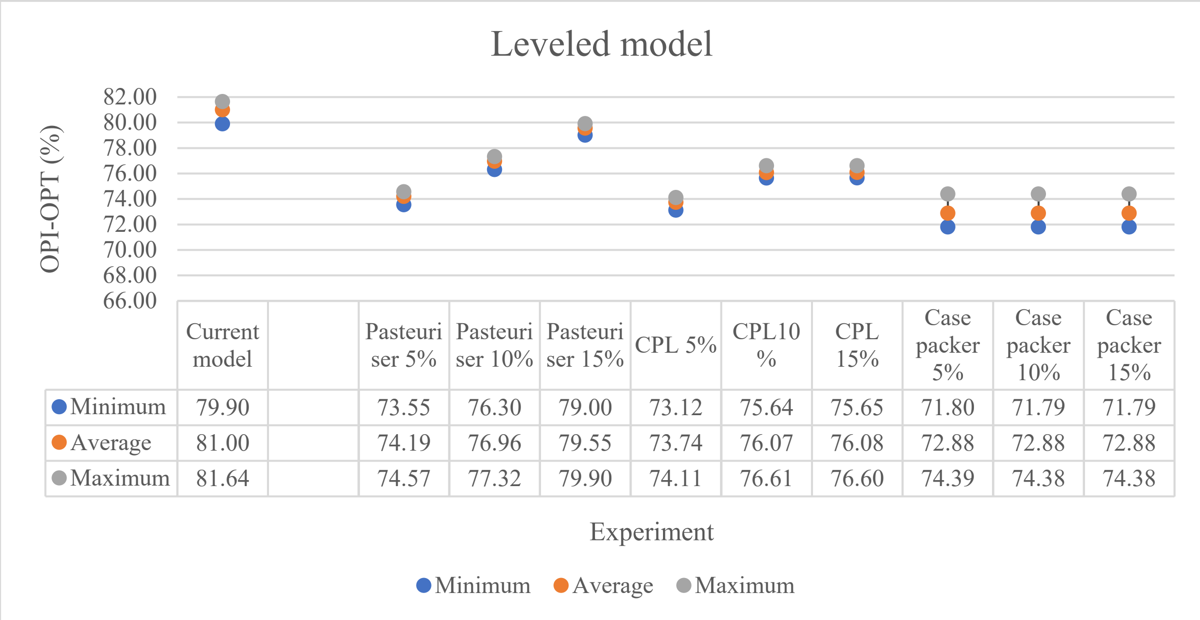


	Current model		Pasteuri ser 5%	Pasteuri ser 10%	Pasteuri ser 15%	CPL 5%	CPL10 %	CPL 15%	Case packer 5%	Case packer 10%	Case packer 15%
Minimum	79.90		80.80	80.78	80.82	79.72	79.83	79.83	76.88	76.85	76.85
Average	81.00		81.86	82.10	82.20	80.26	80.79	80.81	78.12	78.14	78.14
Maximum	81.64		83.04	83.19	83.39	80.90	81.51	81.52	79.82	79.97	79.95

Figure 24: Results reverse sawtooth model

5.1.5 Levelled model

All models for the levelled performed worse than the model that is currently applied at production line 52. The best performing setting for the levelled model is the experiment with the pasteuriser as the bottleneck and step increase of 15%.



	Current model		Pasteuriser 5%	Pasteuriser 10%	Pasteuriser 15%	CPL 5%	CPL10 %	CPL 15%	Case packer 5%	Case packer 10%	Case packer 15%
Minimum	79.90		73.55	76.30	79.00	73.12	75.64	75.65	71.80	71.79	71.79
Average	81.00		74.19	76.96	79.55	73.74	76.07	76.08	72.88	72.88	72.88
Maximum	81.64		74.57	77.32	79.90	74.11	76.61	76.60	74.39	74.38	74.38

Figure 25: Results levelled model

5.1.6 Findings workload model

The best performing experiments for each workload model was based on the pasteuriser as the bottleneck machine with a step increase of 15%. It seems that shifting the lowest processing speed to another machine decreases the output of the production line. The best results of the workload allocation models are shown in Figure 26. The orange line indicates the performance of the current workload model (81,01 %), while the grey line indicates the performance if no model has been set in place and thus all machine's speed is equal to the bottleneck machine.

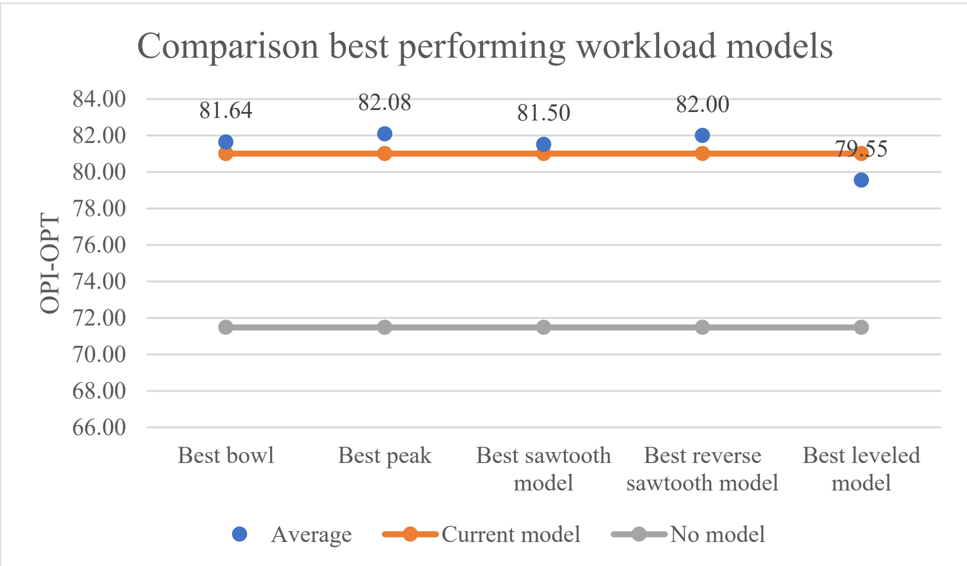


Figure 26: Summary of best-performing workload models

5.2 Overall buffer increase experiments

This section deals with the general buffer increase experiments that were conducted for the models shown in Table 11. The following experiments with regards to an overall buffer increase are conducted: no extra buffer, 10% more buffer, 20% more buffer and 30% more buffer capacity for each machine. For these experiments, five replications were run. The minimum, average and maximum values for the five replications for each experiment are displayed in Table 12. Note that the current model without any extra buffer capacity is the current model that is used at Heineken and is the same as experiment 1 from section 5.1.

Table 12: The results of the experiments for the overall buffer increase

Model	Buffer increase	Minimum	Average	Maximum
Current model	No extra buffer	79,90	81,01	81,63
Current model	10%	81,42	81,83	82,31
Current model	20%	81,69	82,20	82,83
Current model	30%	81,97	82,50	83,20
Bowl model	No extra buffer	81,04	81,78	82,44
Bowl model	10%	81,37	82,57	83,72
Bowl model	20%	81,77	82,96	84,28
Bowl model	30%	82,08	83,28	84,66
Peak model	No extra buffer	80,95	82,27	83,73
Peak model	10%	81,27	82,64	84,27
Peak model	20%	81,68	82,98	84,61
Peak model	30%	82,00	83,25	84,87
Sawtooth model	No extra buffer	81,15	81,64	82,34
Sawtooth model	10%	81,49	82,48	83,23
Sawtooth model	20%	81,83	83,11	84,60
Sawtooth model	30%	82,21	83,44	84,97
Reverse sawtooth model	No extra buffer	80,87	82,19	83,38
Reverse sawtooth model	10%	81,27	82,58	83,93
Reverse sawtooth model	20%	81,67	82,95	84,33
Reverse sawtooth model	30%	81,96	83,26	84,66
Levelled model	No extra buffer	79,00	79,56	79,93
Levelled model	10%	80,62	81,06	81,54
Levelled model	20%	81,62	82,13	82,81
Levelled model	30%	81,93	82,85	83,63

The results of Table 12 are visualised in Figure 27. As can be seen in the figure, an increase in buffer capacity increases the OPI-OPT values for each of the workload models, but some more than others. This is especially seen in the levelled model since this model does not has the difference between producing speed between the machines and therefore is less able to deal with disruptions in the production line. The highest OPI-OPT performance for the current model was achieved with a buffer increase of 30%. This 30% increase let to a 1,49% absolute increase in OPI-OPT.

The best average OPI-OPT performance was achieved with the sawtooth model, with a 30% increase in buffer capacity. This lead to an increase of 2,43% absolute increase in average OPI-OPT performance in comparison to the current model with no buffer.

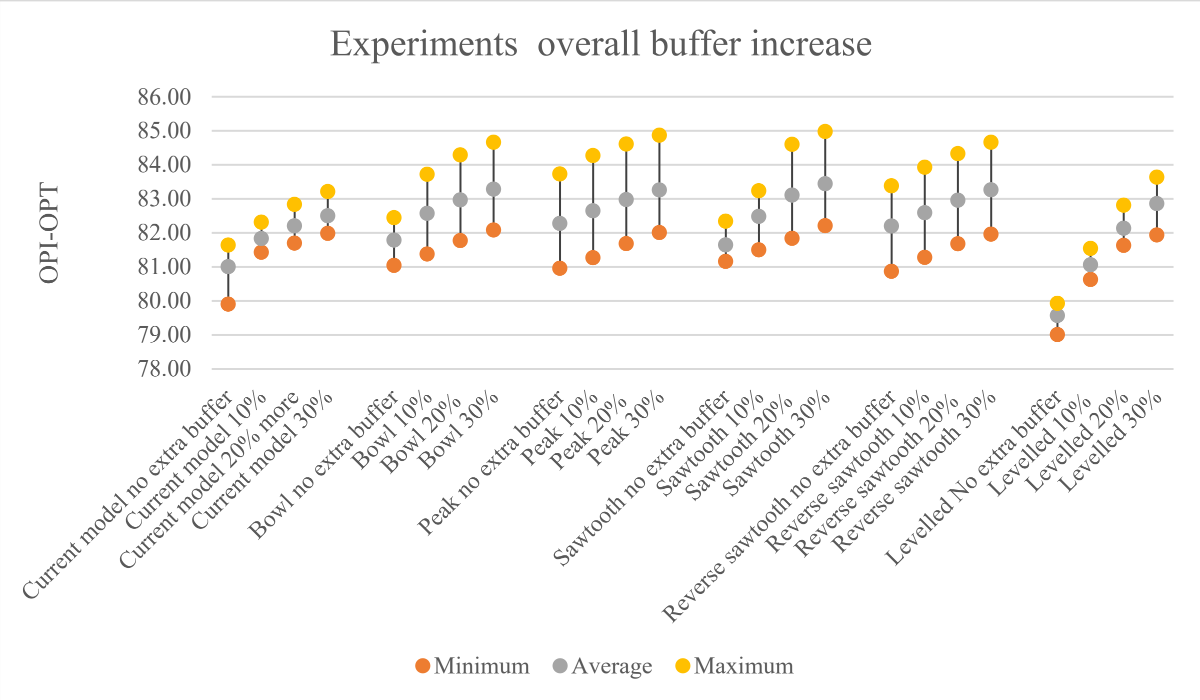


Figure 27: Visualisation of the data for the experiments with overall buffer increase

5.3 Buffer increase in front of specific machines

Besides the overall increase in buffer capacity over the line, also experiments with regards to buffer increase in front of the three possible bottleneck machines of the line are conducted. These are the pasteuriser, the CPL machines and the case packers. For each of the workload models, an increase of 10%, 20% and 30% is tested. The performance of the current model is also shown in the figures in this section to highlight the differences between the performance of the experiments and the current model. Section 5.3.1 shows the performance of the experiments for the buffer increase in front of the pasteuriser; 5.3.2 displays the performance of the experiments in front of the CPL machines; and lastly the results of the experiments for an increase of buffer in front of the case packers are shown in Section 5.3.3. The exact outcome of OPI-OPT value for each experiment are placed in Appendix G.

5.3.1 Buffer increase in front of pasteuriser

The results of the buffer increase experiments in front of the pasteuriser are shown in Figure 28. Remarkably the performance of the model slightly decreases when the buffer in front of the pasteuriser increases. This has most likely to do with the fact that the pasteuriser always needs at least a half-empty buffer in front of the machine before it takes in any WIP. For this reason, more WIP is needed to achieve a 50% fill level, and the pasteuriser thus has to wait slightly more to able to produce. An increase of buffer in front of the pasteuriser may result in higher performance when the fill level required to produce is not static, but this was not tested for the experiments.

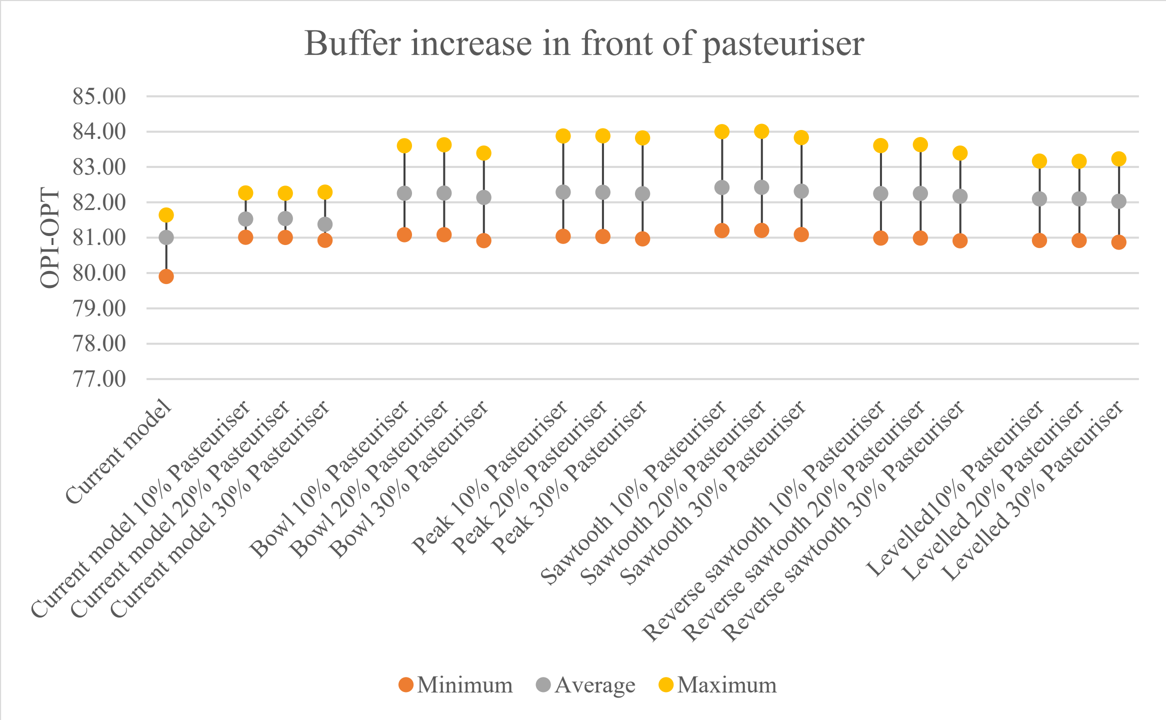


Figure 28: The experiments for an increase of buffer capacity in front of the pasteuriser

5.3.2 Buffer increase in front of CPL

The increase in buffer capacity in front of the CPL machines is shown in Figure 29. Contrary to the increase in buffer capacity in front of the pasteuriser, an increase in front of the CPL machines does increase the average performance of the OPI-OPT metric slightly. All models, including the levelled model, perform better with an extra buffer in front of the CPL machine in place than the current model.

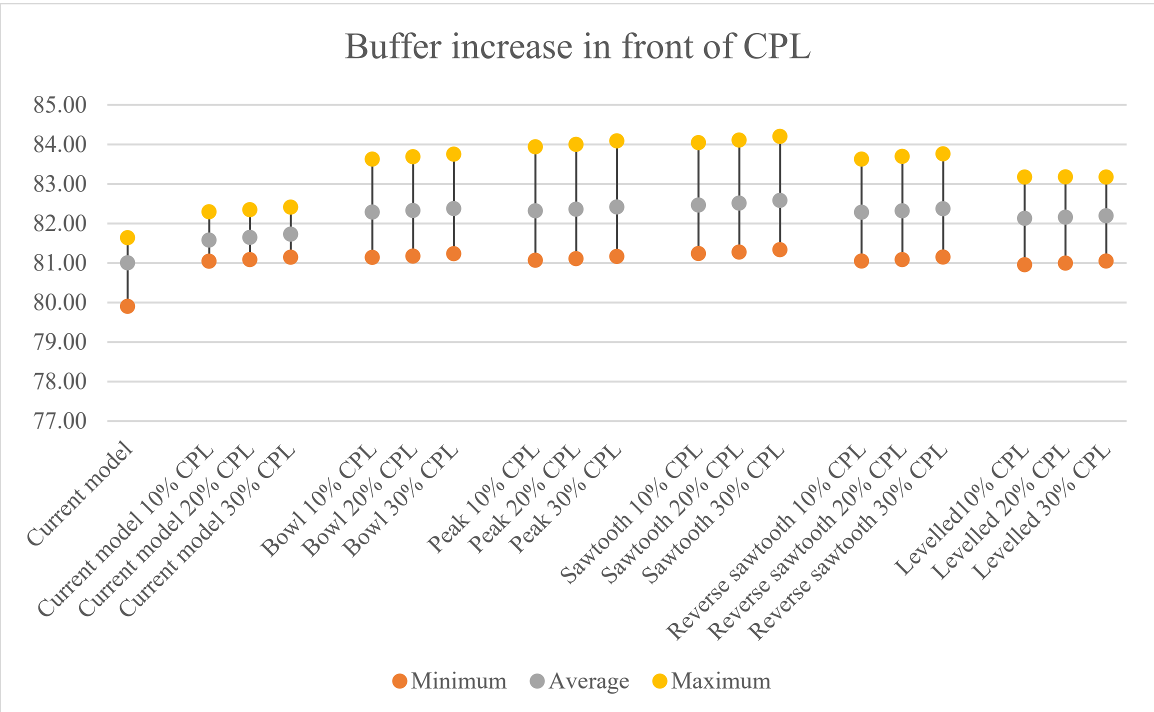


Figure 29: The experiments for an increase of buffer capacity in front of the CPL machines

5.3.2 buffer increase in front of the case packers

The highest differences between the step increase of the buffer can be seen for the experiments of buffer increase for the case packer. Again, all the models perform better than the current model with some extra buffer in place. The sawtooth model achieves the highest average performance for the buffer experiments in front of the case packers with a 30% increase in front of the case packers. The average OPI-OPT value for this experiment was 83,08%.

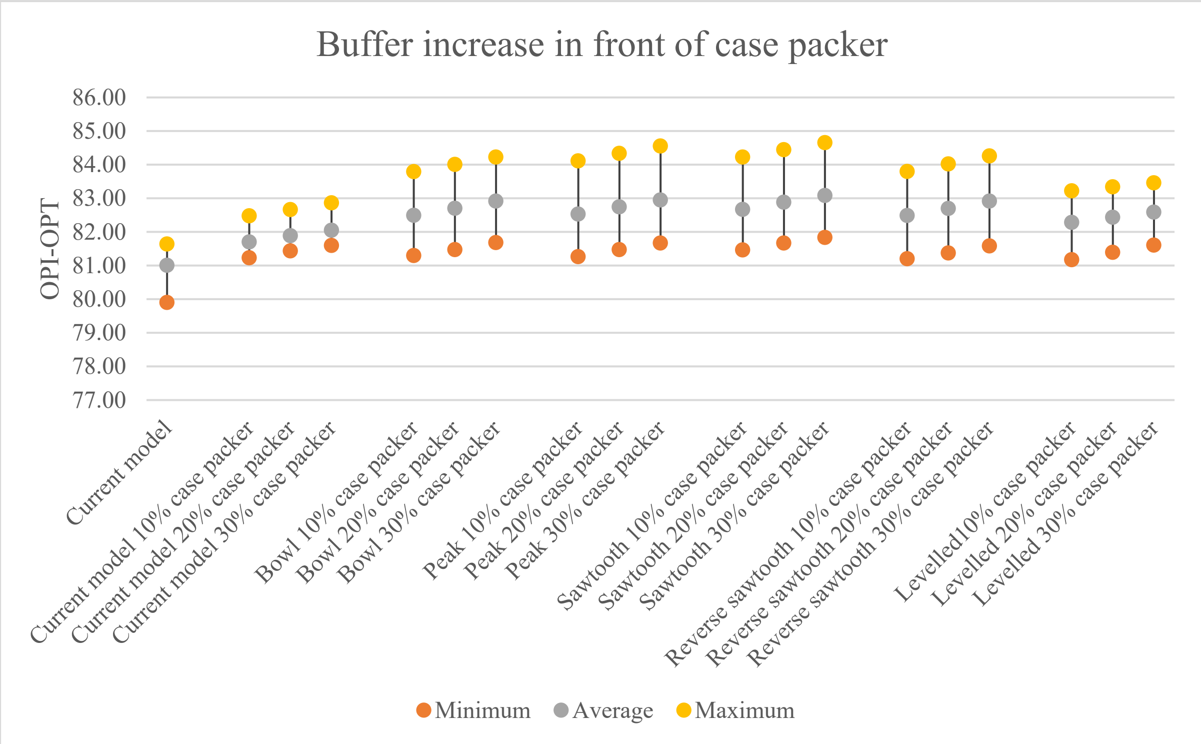


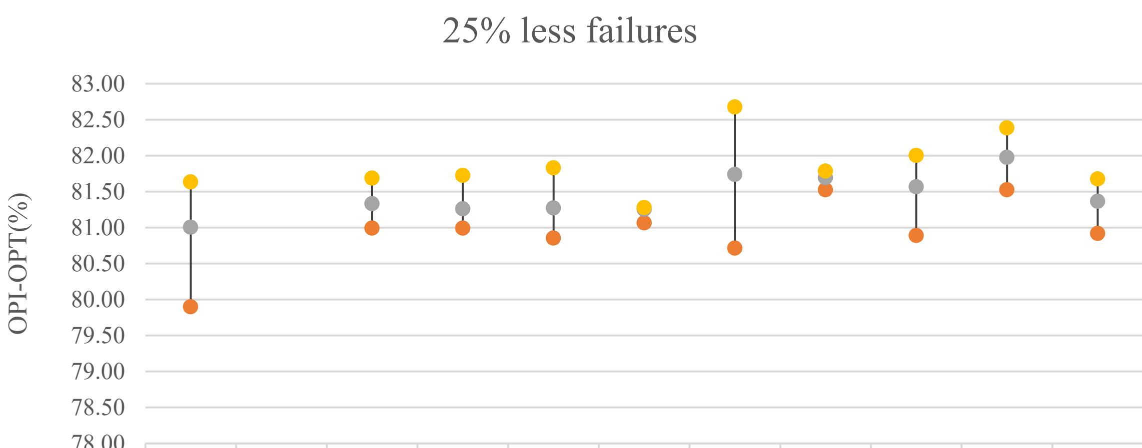
Figure 30: The experiments for an increase of buffer capacity in front of the case packer

5.4 Failure experiments

Six experiments are conducted to evaluate what the effect is of failure or MST reduction for a specific machine on the performance of the system. First, the results of a reduction of failure amount are discussed in Section 5.4.1. The results for a reduction of MST are elaborated in Section 5.4.2. For both experiment types, a reduction of 25%, 50% and 75% is applied. The performance of the current model without any improvement in the failure amount or MST times are included in the figures to compare the improvements over the current model.

5.4.1 Failure amount reduction

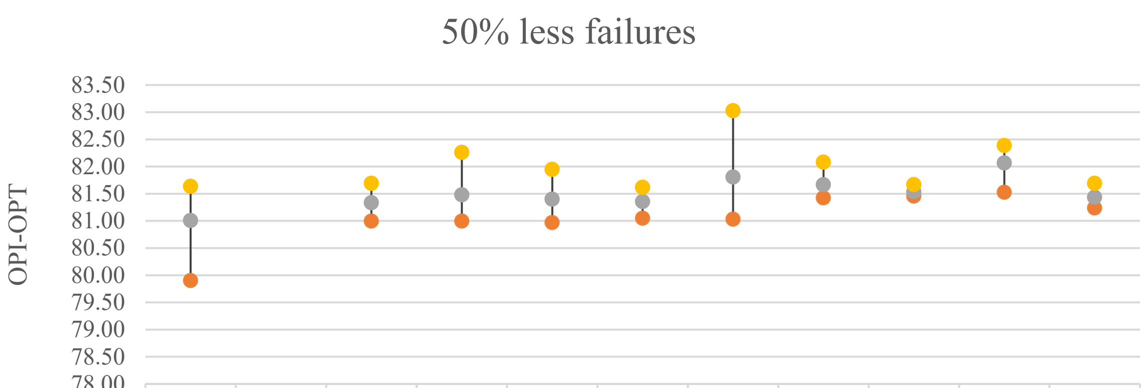
The results of a 25% reduction of failures amount for each machine are shown in Figure 3, while the results of the experiments with a 50% reduction in the number of failures are shown in Figure 32 and 75% reduction in Figure 33. All the experiments show an improvement over the current model for 25%, 50% and 75% reduction in failure amount. The difference between the performance of the 50% and 75% reduction in failure amount is minor. This indicates that it may be sufficient for Heineken to reduce the number of failures for the most critical machine to a certain level and that striving for even fewer failures may not be profitable. The highest performance increase with for all the failure amount reduction experiments is achieved by decreasing the failure amount for the case packer. Significant improvement is also seen for the experiments for the CPL and case erector.



	Current model		Foiling machine	Destacker	Filler	Pasteuriser	CPL	Case erector	Interior placer	Case packer	Case closer
Minimum	79.90		80.99	80.99	80.85	81.06	80.71	81.52	80.89	81.52	80.92
Average	81.01		81.33	81.26	81.27	81.25	81.74	81.69	81.57	81.98	81.37
Maximum	81.63		81.69	81.72	81.83	81.28	82.68	81.79	82.00	82.39	81.68

Minimum Average Maximum

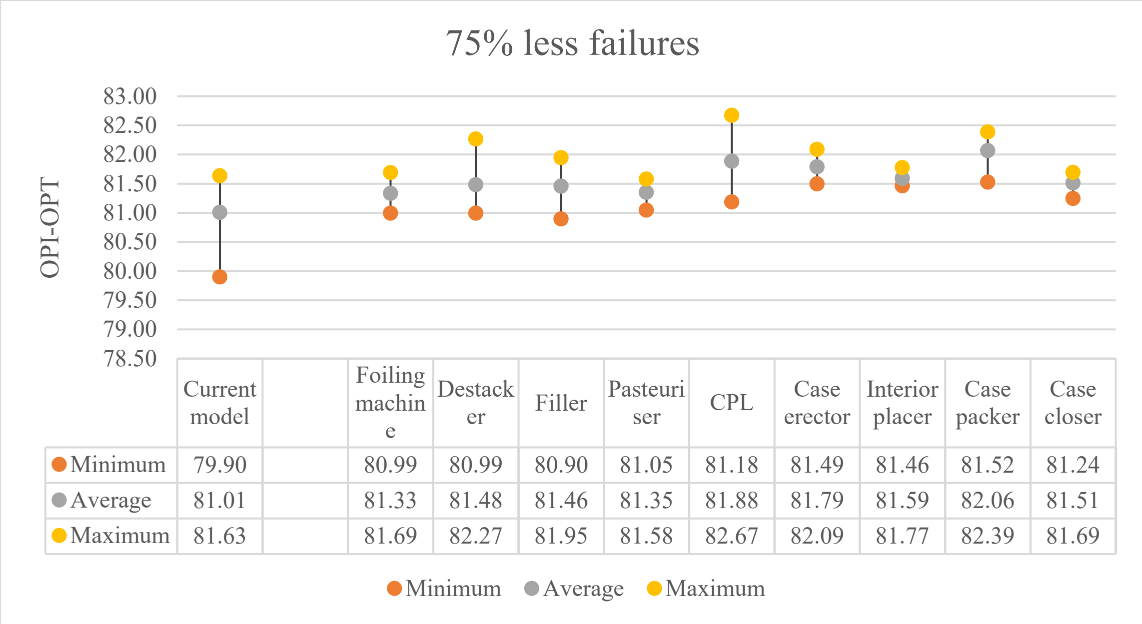
Figure 31: Result 25% reduction of failures per machine



	Current model		Foiling machine	Destacker	Filler	Pasteuriser	CPL	Case erector	Interior placer	Case packer	Case closer
Minimum	79.90		80.99	80.99	80.97	81.05	81.03	81.42	81.45	81.52	81.24
Average	81.01		81.33	81.48	81.40	81.35	81.80	81.66	81.53	82.06	81.43
Maximum	81.63		81.69	82.26	81.95	81.62	83.03	82.08	81.67	82.39	81.69

Minimum Average Maximum

Figure 32: Result 50% reduction of failures per machine

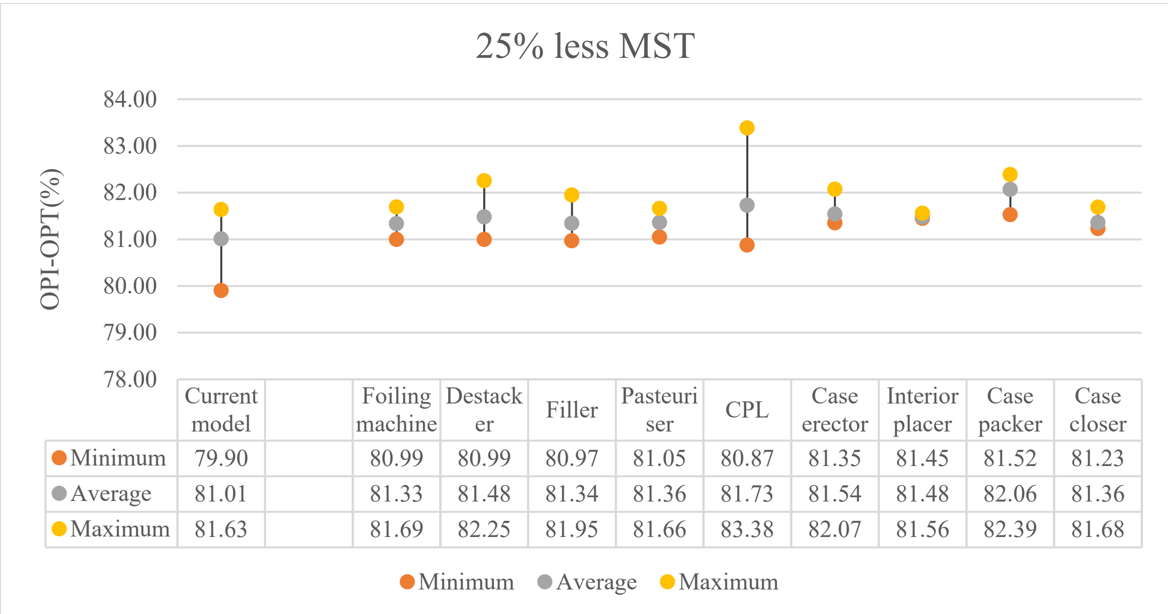


	Current model		Foiling machine	Destacker	Filler	Pasteuriser	CPL	Case erector	Interior placer	Case packer	Case closer
Minimum	79.90		80.99	80.99	80.90	81.05	81.18	81.49	81.46	81.52	81.24
Average	81.01		81.33	81.48	81.46	81.35	81.88	81.79	81.59	82.06	81.51
Maximum	81.63		81.69	82.27	81.95	81.58	82.67	82.09	81.77	82.39	81.69

Figure 33: Result 75% reduction of failures per machine

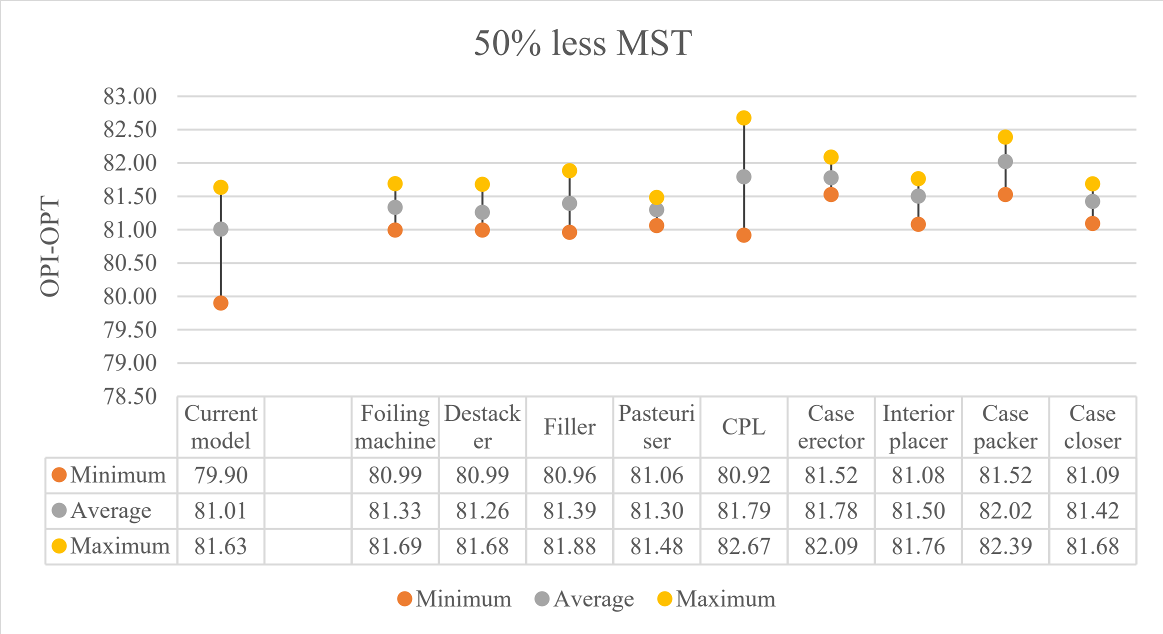
5.4.2 MST reduction

The experiments with a 25% reduction of MST are shown in Figure 34, 50% reduction of MST in Figure 35 and lastly the 75% reduction for MST are shown in Figure 36. Also for these experiments can be seen that the differences between the 25%, 50% and 75% experiments are small. For all the experiments the highest performance is achieved by the case packer, while the experiments for the CPL and the case erector performed second and third best respectively. The differences between the reduction experiments for the failure amount and the MST reduction experiments are minor.



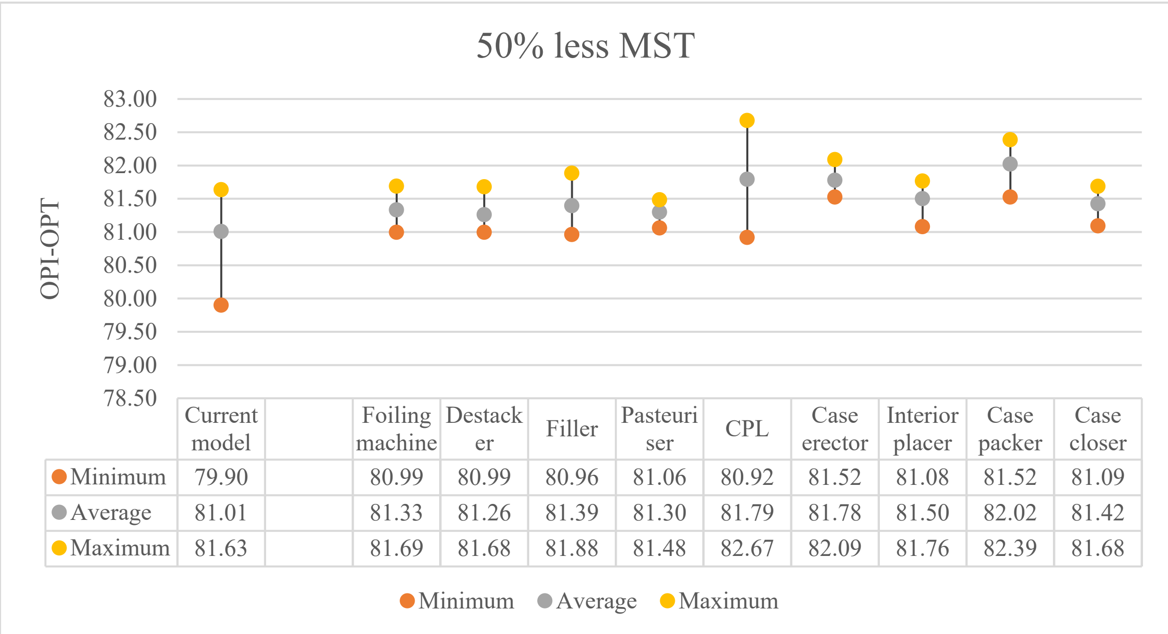
	Current model		Foiling machine	Destacker	Filler	Pasteuriser	CPL	Case erector	Interior placer	Case packer	Case closer
Minimum	79.90		80.99	80.99	80.97	81.05	80.87	81.35	81.45	81.52	81.23
Average	81.01		81.33	81.48	81.34	81.36	81.73	81.54	81.48	82.06	81.36
Maximum	81.63		81.69	82.25	81.95	81.66	83.38	82.07	81.56	82.39	81.68

Figure 34: Result 25% reduction of MST per machine



	Current model		Foiling machine	Destacker	Filler	Pasteuriser	CPL	Case erector	Interior placer	Case packer	Case closer
Minimum	79.90		80.99	80.99	80.96	81.06	80.92	81.52	81.08	81.52	81.09
Average	81.01		81.33	81.26	81.39	81.30	81.79	81.78	81.50	82.02	81.42
Maximum	81.63		81.69	81.68	81.88	81.48	82.67	82.09	81.76	82.39	81.68

Figure 35: Result 50% reduction of MST per machine



	Current model		Foiling machine	Destacker	Filler	Pasteuriser	CPL	Case erector	Interior placer	Case packer	Case closer
Minimum	79.90		80.99	80.99	80.96	81.06	80.92	81.52	81.08	81.52	81.09
Average	81.01		81.33	81.26	81.39	81.30	81.79	81.78	81.50	82.02	81.42
Maximum	81.63		81.69	81.68	81.88	81.48	82.67	82.09	81.76	82.39	81.68

Figure 36: Result 75% reduction of MST per machine

5.4.3 Most critical failures

The most important machines for failure improvement are the case packer, case erector and the CPL machines. The failures that influence the amount of downtime of the line the most are discussed in this section to highlight possible areas of improvement for the number of failures of the machines. These are based on the data registration program MES. Some of the names that are given to the failure are vague or is a consequence of a problem such as an open door of a machine because an inspection of the problem is needed by an operator. Therefore the most occurring and critical failures of each machine were discussed with an operator. First, the most occurring errors for the CPL machines is discussed. Next, the failures of the case erector are presented and lastly the case packer.

The machine failure that is taking up the most failure time for the CPL machine is that the bottle was not in the right position when the label was placed on the bottle. The inspection machine after the

CPL machine detects the placement of this bottle and ejects this bottle.

The most critical failure for the case erector is that the cases are placed correctly on the start of the belt. The suction caps of the case erector can, therefore, erect the box less well, and this may cause problems further on the line. A problem often seen in the past was that two boxes at a time were pushed on the start of the belt. This caused the upper box to be erected while the box beneath it was not erected. By lowering the maximum height of the infeed of the case erector this problem is not often seen anymore.

The problems that the case packer faces mostly originated somewhere else in the line. When a broken bottle is not detected by an inspection machine, a broken bottle can end up at the infeed of the case packers. A failure that is most often seen for the smaller bottle type is that the broken bottle is detected at the case packers and needs to be removed before the machine can continue. A problem more often seen for the 355 ml bottle is that two bottles enter the infeed of the case packers causing the bottle to be stuck since the infeed width is not enough to support the width of two 355 ml bottles. Lastly, a problem which is sometimes seen for the case packer is that not two boxes enter the case packer at the same time. Each case packer fills two boxes at the same time with bottles. If only one box has entered the machine, the machine indicates an error and stops working till two boxes are located in the case packer.

5.5 Summary results

In this chapter, the results of the experiment were shown. Section 5.1 dealt with the optimal workload allocation model. It was demonstrated that all the proposed models, with the exception of the levelled workload model, performed better than the current model. The best workload model based on the average OPI-OPT performance is the peak model with a 30% step increase, closely followed by the reverse sawtooth model, also with a 30% step increase. The peak model, with a 30% step increase improved the average value of OPI-OPT from 81,01% to 82,28%.

In Section 5.2, experiments for an increase of overall buffer amount were conducted. Increasing the buffer amount in front of all the machines increased the average performance of OPI-OPT. For the current model that is applied at Heineken, increasing the buffer amount with 10%, 20% and 30% resulted in an absolute increase of 0,82%, 1,19% and 1,49% respectively. The highest performance was achieved with the best sawtooth model with an increase of 30%, which resulted in an average OPI-OPT performance of 83,44% OPI-OPT in comparison with the current 81,01% performance.

Section 5.3 dealt with experiments with an increase of buffer in front of specific machines. Increasing the buffer in front of the pasteuriser did not increase the performance of the production line, since the pasteuriser needs more WIP on the buffers before it operates. Placing more buffer in front of the case packer showed the most increase in performance of the average OPI-OPT value. The best performing experiment was the sawtooth model with a step increase of 30% in front of case packer. The average value of this experiment was 82,51%, which is only slightly lower than the performance of a 30% overall buffer increase of 83,44%.

Lastly, experiments concerning failure and MST reduction were conducted. The differences between the experiments for MST and failure amount showed only minor differences. The increase in productivity for the 25%, 50% and 75% experiments for both experiments. The failure experiments show the most critical machines for the improvement of the production line. As can be seen in results of Section 5.4.1 and 5.4.2, the improvements that generated the highest performance increase when either the MST or the number of failures are reduced by half are the case packer, case erector and the CPL machines. Section 5.4.3 showed the most critical failure for those machines according to the operators.

6

Criteria and implementation for advice

This chapter analyses the criteria for the best advice for Heineken and the steps that are required for the implementation of the solution. Section 6.1 shows the criterium for the best solution for Heineken. The most important criterium is the profit increase that comes with the implementation of the solution. The cost-benefit analysis for the best scoring experiments is evaluated in Section 6.2. The implementation of the best scoring solutions is discussed in Section 6.3. Last, the conclusion of the chapter is given in Section 6.4.

6.1 Criteria for the best solution

Heineken uses a rule for the implementation of the solutions: if the solution is expected to not be profitable within X years, the solution is not interesting for Heineken. Especially in these uncertain and unpredictable times with the outbreak of the COVID-19 virus, the management of production line 52 sticks to this rule. According to my Heineken supervisor, the criteria for the best solution are the following:

- The productivity increase that the solution generates for the production line is the most important criterium. Increasing the productivity of the line will increase the profit of the production. If the profit is higher than the expected implementation costs, Heineken is expected to earn more profit from the solution in comparison with the current situation in the X year period. For each of the best scoring solutions, a cost-benefit analysis has been conducted in Section 6.2 to see what the net profit effects are for the solutions.
- Related to the costs of the implementation is the risk involved in unexpected outcomes. Heineken presumes that increasing the production speed of the machines will increase the wear and tear of the machines over time. Since there is no data about the relationship between the speed of the machines and the wear and tear, the costs for this wear and tear is not included in the cost-benefit analysis. The possible side-effects of the solutions are, however, included in the discussion of the results for the decision making of Heineken.
- It should be possible for Heineken to implement the solution to the production line. The workload models were adapted to the maximum possible speed for the machines of the production line.

  The possibility for buffer increase is lesser-known. Increasing the buffer amount in front of the machines requires either a new machine or new layout for the production line. Since it was not known beforehand what level of buffer amount can be attained at maximum for each machine, we have taken the 30% buffer increase as the maximum level of buffer that the buffers in front of the machines can attain.

  Lastly, the failure reduction experiments act merely as advice for Heineken for what machine they should focus on for the reduction of failures and their failure times. Reducing the number of failures of the recommended machines will lead to the most increase in productivity of the machines in the line. The feasibility of reaching the reduction levels of the experiments is not known.

6.2 Cost-benefit analysis

The criterium for the solution was explained in Section 6.1 The most important criterium for the solution is based on the cost and benefit of the solution. For that reason, a cost-benefit analysis of the best resulting solution based on OPI-OPT is analysed for each experiment type.

Table 13 shows the costs and benefits associated with the implementation of the best scoring workload models. The cost for the implementation of the workload models is based on the number of changes that are needed based for the machines. For all the workload models, the speed of the pasteuriser does not have to change, while the speed of all the other nineteen machines has to change. Since the cost for changing the processing speed of the machines has been estimated to be X euros per machine in Section 2.6, the cost for the implementation of the workload models is thus equal to 19*X = 19*X euros.

This cost of the implementation will likely be lower for two reasons: the difference between the speed of the new workload model and the current model is minor. Changing the speed of those machines may therefore not be necessary. Another reason that the cost could be lower for the implementation is that the cost is based on the number of changes needed times the price for one machine speed change. It could be possible that the cost of changing the speed of multiple machines may be lower due to a discount.

Since this workload model increases the productivity the most in comparison with the current model and the costs for the implementation of the models are assumed to be the same, the most profit is generated by implementing the peak model. This model increases the average OPI-OPT by 1,24% and leads to an extra profit of X euros in X years for Heineken.

Table 13: Cost-benefit for best settings for the workload models

Workload model	OPI-OPT increase	Cost	Benefit	Profit
Bowl	0,63			
Peak	1,07			
Sawtooth	0,49			
Reverse sawtooth	0,99			
Levelled	-1,46			

The cost-benefit analysis for the buffer increase experiments is shown in Table 14. The 30% buffer increase experiment for all the buffer increase experiments for all machines showed the most increase in productivity in comparison with the current model, while the experiments for the individual buffer increase showed the most increase if the case packers have 30% more buffer capacity.

Changing the buffer amount in front of a machine is estimated to cost around X euros. The difference between the 30% buffer increase for all the buffers and a 30% buffer increase in front of the case packer is small while the cost difference is large. Increasing the buffer in front of the case packers is profitable from the second year on. While the difference in profit generated by the 30% more buffer in front of case packer is lower than the peak model, the risks of more wear and tear are lower since the speed of the machines is kept the same.

Table 14: Cost-benefit for best buffer experiments

Buffer	OPI-OPT increase	Cost	Benefit	Profit
30% Overall buffer increase	1,71			
30% More buffer case packers	1,2			

Lastly, the possible profits for the failure reductions for the case packers, CPL machines and the case erector are presented. Since the results of reducing the failure amount and decreasing the failure times with the same percentage showed minor differences in the outcome of the KPI, I have chosen only to show the cost-benefit analysis for the reduction of failures.

Since it is difficult to estimate the cost of improving the failure amount of the machines, the cost is left out of Table 15. It could be possible that knowing what currently the most important machines for improvements in MST and failure generation could lead to an improvement of productivity since these machines are then more prioritised. Heineken could also find solutions based on the most frequent failures to reduce the number of failures of the three machines presented in Table 15.

Table 15: Cost-benefit for best failure reduction experiments

Failure	OPI-OPT increase	Benefit	Profit
50% Reduction failures case packer	1,21		
50% Reduction failures CPL	0,92		
50% Reduction failures case erector	0,75		

6.3 Implementation plan

In this section, the implementation of the experiments is discussed. The implementation of the experiment types are discussed in the following order: workload experiments, buffer experiments and lastly the failure experiments.

In table 16, an example of the schedule for the implementation of the workload models is shown. At least two days are needed for the implementation of the workload model. Since production line 52 fills three types of bottles, the procedure for the implementation has to be done three times. The schedule for the implementation of the workload speeds is the same for all the bottle types, except that a different bottle type is tested for each of the repetitions. In the morning or the night before the first day of the implementation, the production line may need a change-over to be able to produce the required bottle type. In the morning of the first day of the implementation, the proposed production speed is implemented one machine by one. Together with the supplier and the quality control department of Heineken is checked if the machines can attain the minimum quality requirements of the machines. The operators and the mechanics are present to see what changes are done to the machines. When all the machines have been checked, Heineken switches back to the old settings for the machines in the evening and night shift since the supplier cant be there at the production line during those times. If the minimum quality requirements are met, the production line is changed to its old workload model since the supplier of the machines can not be at the production line during the evening and night shifts.

In the morning of the next day, the proposed workload model is applied to the production line again. This time is checked if the production line is achieving a higher productivity output. The supplier is needed to apply the changes in the production line again. After the morning shift is determined if the new model is achieving a higher productivity output; if this is the case, the new workload model will be used for this bottle type in the future. This procedure is repeated for the other two bottle types.

Table 16: Example of schedule for implementation of the workload models.

Day	Shift	Task	Required people
Monday	morning	Implementation proposed workload speed	Supplier, operator, mechanic, quality control
	Evening	Return to the old schedule	Operator
	Night	Return to the old schedule	Operator
Tuesday	morning	Check the performance of the line	Supplier, operator
	Evening	New model	Operator
	Night	New model	Operator
Wednesday	morning	Implementation proposed workload speed	Supplier, operator, mechanic
	Evening	Return to the old schedule	Operator
	Night	Return to the old schedule	Operator
Thursday	morning	Check the performance of the line	Supplier, operator
	Evening	New model	Operator
	Night	New model	Operator
Monday	morning	Implementation proposed workload speed	Supplier, operator, mechanic
	Evening	Return to the old schedule	Operator
	Night	Return to the old schedule	Operator
Tuesday	morning	Check the performance of the line	Supplier, operator
	Evening	New model	Operator
	Night	New model	Operator

There are two ways for the buffer experiments to implement the solution. The line could be widened to fit more bottles on the line, or a new line could be purchased. When the first option is chosen, the line should be widened during the maintenance periods of the production line to overcome that planned production is not able to be produced and thereby save costs. The new line should fit within the line layout of the production line and is the widening is done by a technical person of the line supplier. The second option is more expensive but may be needed when the line can not be widened because of the structure of the line.

The feasibility of the failure experiments is not known. Improvements in the machines and reductions in the failure times or failure amounts are achieved by continuous improvements in the TPM protocols. The Pareto-analysis is used to find the most occurring errors for a machine, and improvements are made based on the most critical failures found for this machine.

6.4 Conclusion Chapter 6

This chapter analysed the criterium for the best solution. The most important criterium for the solution is based on the increase in profit that will be generated by implementing the solution for an X year period. The experiments that showed the most increase in productivity were analysed based on the implementation costs and the profit that is expected to be generated with the increase of productivity in comparison with the current model that is used for production line 52.

The most profit can be generated by implementing the peak model, but there are some risks involved in implementing the solution. The buffer experiment showed a modest increase in profit, but I expect that the implementation will result in less unknown side effects. Lastly, the failure reduction experiments showed the most important machines for failure reduction. Reducing the failures of the case packers showed to be especially lucrative. Decreasing the number of failures generated by the case packers results in a profit of X euros in an X year period. However, the costs and feasibility of this implementation are not known.

Lastly, the implementation of the experiments was discussed. Heineken has a standard protocol for the implementation of the new processing speed of the machines and was described in Section 6.3. There are two options for the implementation of the buffer experiments which depends on the possibilities within the factory to widen the buffer. If this is not possible within the system, a new, more expensive line could be purchased. Lastly, the failure experiments could be achieved by continuous improvements of TPM.

7

Conclusion and recommendations

This last chapter provides the conclusion and discussion for the research and gives recommendations for further research and Heineken. The conclusion of the research is given in Section 7.1, while the discussion of the results is discussed in Section 7.2. The recommendations for Heineken and further research are given in Section 7.3.

7.1 Conclusion

The research of this thesis assignment was focussed on finding ways for improvement of production line 52. In this section, the research is concluded by answering the research questions presented in Section 1.5:

1. *How is the performance of production line 52 defined, and how can this be measured?*

This research focussed on finding improvements for the productivity of the line. Since the choice has been made to focus on stops shorter than five minutes, the metric OPI-OPT has been derived from the metric OPI-Nona that is used by Heineken. The value of OPI-OPT and OPI-Nona can be calculated with the information available in MES reporting. The value of OPI-OPT is calculated by dividing the production time by the operation time, while the value of OPI-Nona is calculated by dividing the theoretical production time by the effective working time.

2. *How can the productivity of a production line be enhanced? Which of them are relevant for this research?*

Based on the literature research and the empirical findings at Heineken Zoeterwoude, three types of improvements for the line were found: a different workload model, increasing the buffer amount in front of the machines and improving the failure patterns of the machines. The theory of constraints methodology is used throughout the report to elevate the constraint of the productivity of the line.

3. *What information is needed for the conceptual model?*

The conceptual model consists of two parts: the first part is a list of all the inputs of the system, the output of the simulation and the assumptions and simplifications that are taken for the simulation model. The second part encompasses the event logic flow, which presents the possible events in the simulation model and the consequences of the events. The processing speed of the machines, failure patterns of the machine, buffer amounts and time to move from end to the other end on the buffer were needed for the input of the conceptual and simulation model. Also, the maximum possible speed was needed for each machine. The data was retrieved from a combination of empirical research, interviews with operators, and MES reporting. The experiments for the simulation are based on the constraints of the system and the possible ways for improvement as found for research question 2. The assumptions and simplifications are based on the interviews and the guided tours provided by the operators.

4. *What advice can be given to Heineken based on the outcomes of the simulation study?*

The advice for Heineken is two-fold: the buffer and workload model experiments were designed to advise on physical or software changes to production line 52, while the failure experiments functioned to give insight in the most critical machines for failure or MST reduction.

Purely based on the outcomes of the simulation model and the assumed associated costs, it may be profitable to install more buffer capacity in front of the case packers in the long term. When an X-year horizon is considered, this solution may not be very appealing for Heineken since the expected profit is relatively low in comparison with other solutions. For the workload model, the best solution seems to be the peak model. The costs for implementation are most likely lower than the high current estimate, and applying this solution will still generate an extra X euros for the first year of the implementation.

According to the failure experiments, the most critical machines for improvement in the number of failures or MST are the case packers, case erectors and the CPL machines. Decreasing the number of failures of those machines can increase productivity and thereby the profit of production line significantly.

5. *What steps need to be taken to implement the solution?*

The steps that need to be taken to implement the solution depend on the choice of solution. Software changes can implement the workload models. These software changes can be done by a specialist of the supplier of the relevant machines.

Increasing the buffer amount in front of the machines may be a more challenging task. A production layout is needed for the new conveyor belt. If it is not possible to increase the width or length of the conveyor belt, as the current conveyor belt needs to be broken down, and a new conveyor belt has to be set into the place. The safety rules and constraints of the facility should also be taken into account.

Several steps could be taken for the implementation of the improvements of the failures. Using the Pareto analysis to tackle the most occurring failures for the machines could help to decrease the number of failures of the machines. Getting a deeper understanding of most occurring failures and teaching the operators how they can effectively tackle these problems may help to bring the MST for the machines down.

7.2 Discussion

The results and validation of the results are discussed in this section. The assumptions that have been taken and the approach of this research have consequences for the reliability of the results and thus, the advice that is given to Heineken Zoeterwoude. Since it is impossible to discuss all the possible unknown effects and assumptions of the research, only the most important ones are discussed.

First and foremost, the effect of a changed production speed on the health of the machines is not known. The assumption is taken that an increased production speed results in wear and tear and therefore increases the number of failures over the line, but the extent of this is not known. The proposed changes for the production speed may, therefore, not lead to an increase in productivity or even decrease the productivity levels. It is up to Heineken if they think that changing the production speed of the machines in production line 52 is worth the risk of more failures.

Second, the advice on the results of the simulation model is based on the assumption that the simulation model imitates the real production line accurately. With the help of black-box and white box validation technique and the help of two external simulation model experts who both work with Siemens Plant Simulation, the simulation model has been validated.

Third, the research focusses solely on the line's ability to deal with short stoppages. It may be possible that the solutions perform differently when all the possible failures are taken into account.

Lastly, the changes to the system are based on the average data of production line 52 for the first half-year of 2020. When significant changes are made to the system, the proposed advice may not be valid anymore.

7.3 Recommendations

In this last section, my personal recommendation for general improvement is presented. First, the recommendation for Heineken is shown based on my own experiences during the internship. Next, the recommendations for further research for this thesis assignment is explained.

7.3.1 Recommendation Heineken

The proposed workload models showed an increase in productivity compared to the current bowl model that is used for production line 52. It may be possible that the increased productivity also holds for different lines of Heineken or companies that use a production line to produce their goods.

According to an operator, the knowledge and skills of the operators on production line 52 vary greatly. It may be interesting for Heineken to find out how they can educate the operators to more skilful workers. This will decrease the amount of failure and the time that is needed to fix the failures since they will have more knowledge of the failures.

Most of the basic information that was needed for the report was not available, including, e.g., the simulation model from the thesis of De Vries (2019). Obtaining the required data was time-consuming. It would save much time for future research by Heineken or graduates if more information, as the production speed of the machines and the buffer amount, were well documented.

7.3.2 Recommendation for further research

The relationship between production speed and failure amount is not known, which influence the outcome of the proposed changes. It may be interesting to find the relationship between the wear and tear of the machines and the production speed of the machines. The choice has been made only to include failures shorter than five minutes. It may be possible that the experiments give different results when all the failures are included.

References

Ahuja, I. P. S., & Khamba, J. S. (2008). Total productive maintenance: literature review and directions. *International journal of quality & reliability management*.

Alizon, F., Shooter, S. B., & Simpson, T. W. (2009). Henry Ford and the Model T: lessons for product platforming and mass customization. *Design Studies, 30*(5), 588-605. doi:https://doi.org/10.1016/j.destud.2009.03.003

Ameen, W., AlKahtani, M., Mohammed, M. K., Abdulhameed, O., & El-Tamimi, A. M. (2018). Investigation of the effect of buffer storage capacity and repair rate on production line efficiency. *Journal of King Saud University - Engineering Sciences, 30*(3), 243-249. doi:https://doi.org/10.1016/j.jksues.2018.03.001

Amiri, M., & Mohtashami, A. (2012). Buffer allocation in unreliable production lines based on design of experiments, simulation, and genetic algorithm. *The International Journal of Advanced Manufacturing Technology, 62*(1), 371-383. doi:10.1007/s00170-011-3802-8

Baker, K. R. (1992). Tightly-coupled production systems: Models, analysis, and insights. *Journal of Manufacturing Systems, 11*(6), 385-400. doi:https://doi.org/10.1016/0278-6125(92)90031-A

Battaïa, O., & Dolgui, A. (2013). A taxonomy of line balancing problems and their solutionapproaches. *International Journal of Production Economics, 142*(2), 259-277. doi:https://doi.org/10.1016/j.ijpe.2012.10.020

Becker, C., & Scholl, A. (2006). A survey on problems and methods in generalized assembly line balancing. *European Journal of Operational Research, 168*(3), 694-715. doi:10.1016/j.ejor.2004.07.023

Becker, C., & Scholl, A. (2006). A survey on problems and methods in generalized assembly line balancing. *European Journal of Operational Research, 168*(3), 694-715. doi:https://doi.org/10.1016/j.ejor.2004.07.023

Boysen, N., Fliedner, M., & Scholl, A. (2008). Assembly line balancing: Which model to use when? *International Journal of Production Economics, 111*(2), 509-528. doi:https://doi.org/10.1016/j.ijpe.2007.02.026

Coccia, M. (2017). The Fishbone diagram to identify, systematize and analyze the sources of general purpose technologies. *4*, 291-303. doi:10.1453/jsas.v4i4.1518

Cooper, D., & Schindler, P. (2014). Business Research Methods.© The McGraw– Hill Companies. 89.

Craighead, C. W., Patterson, J. W., & Fredendall, L. D. (2001). Protective capacity positioning: Impact on manufacturing cell performance. *European Journal of Operational Research, 134*(2), 425-438. doi:https://doi.org/10.1016/S0377-2217(00)00266-6

El-Rayah, T. E. (1979). The efficiency of balanced and unbalanced production lines. *International Journal of Production Research, 17*(1), 61-75. doi:10.1080/00207547908919595

Fleischer, J., Weismann, U., & Niggeschmidt, S. (2006). Calculation and optimisation model for costs and effects of availability relevant service elements. *Proceedings of LCE*, 675-680.

Flores, R., Silva, R., Renelson, R., Sampaio, R., & Passos, F. (2016). Designing Unbalanced Assembly Lines: A Simulation Analysis to Evaluate Impacts on Work-In-Process Results. *6*, 2248-962238.

Goldratt, E. M., & Cox, J. (1984). *The goal: excellence in manufacturing*: North River Press.

Goldratt, E. M., & Cox, J. (2016). *The goal: a process of ongoing improvement*: Routledge.

Habets, R. J. (2019). Improving the line performance of packaging line 41 at Heineken Zoeterwoude : a case study at Heineken. In.

Hillier, F. S. (1966). The effects of some design factors on the efficiency of production lines with variable operation times. *Journal of Industrial Engineering, 17*(12), 651-658.

Hillier, F. S., So, K. C., & Boling, R. W. (1993). Notes: Toward Characterizing the Optimal Allocation of Storage Space in Production Line Systems with Variable Processing Times. *Management Science, 39*(1), 126-133. doi:10.1287/mnsc.39.1.126

Hudson, S., McNamara, T., & Shaaban, S. (2015). Unbalanced lines: where are we now? *International Journal of Production Research, 53*(6), 1895-1911. doi:10.1080/00207543.2014.965357

Karwan, K. R., & Philipoom, P. R. (1989). A Note on "Stochastic Unpaced Line Design: Review and Further Experimental Results". *Journal of Operations Management, 8*(1), 48-54. doi:10.1016/S0272-6963(89)80005-1

Kose, S. Y., & Kilincci, O. (2015). Hybrid approach for buffer allocation in open serial production lines. *Computers & Operations Research, 60*, 67-78. doi:https://doi.org/10.1016/j.cor.2015.01.009

Kyselová, L., & Brányik, T. (2015). 20 - Quality improvement and fermentation control in beer. In W. Holzapfel (Ed.), *Advances in Fermented Foods and Beverages* (pp. 477-500): Woodhead Publishing.

Lande, M., Shrivastava, R., & Seth, D. (2016). Critical success factors for Lean Six Sigma in SMEs (small and medium enterprises). *The TQM Journal, 28*, 613-635. doi:10.1108/TQM-12-2014-0107

Law, A. M., Kelton, W. D., & Kelton, W. D. (2000). *Simulation modeling and analysis* (Vol. 3): McGraw-Hill New York.
Law, A. M., & McComas, M. G. (1991). *Secrets of successful simulation studies.* Paper presented at the Proceedings of the 23rd conference on Winter simulation.
Lee, J.-H., Chang, J.-G., Tsai, C.-H., & Li, R.-K. (2010). Research on enhancement of TOC Simplified Drum-Buffer-Rope system using novel generic procedures. *Expert Systems with Applications, 37*(5), 3747-3754. doi:https://doi.org/10.1016/j.eswa.2009.11.049
Li, L., Chang, Q., & Ni, J. (2009). Data driven bottleneck detection of manufacturing systems. *International Journal of Production Research, 47*(18), 5019-5036. doi:10.1080/00207540701881860
Li, Y., Chang, Q., Xiao, G., & Arinez, J. (2015). Data-Driven Analysis of Downtime Impacts in Parallel Production Systems. *IEEE Transactions on Automation Science & Engineering, 12*(4), 1541-1547. doi:10.1109/TASE.2015.2443111
Ljungberg, Õ. (1998). Measurement of overall equipment effectiveness as a basis for TPM activities. *International Journal of Operations & Production Management, 18*(5), 495-507.
Lopes, T., Michels, A., Lüders, R., & Magatão, L. (2019). A Simheuristic Approach for Throughput Maximization of Asynchronous Buffered Stochastic Mixed-Model Assembly Lines. *Computers & Operations Research, 115*, 104863. doi:10.1016/j.cor.2019.104863
Lopez, C. E. (2014). Unbalanced Workload Allocation in Large Assembly Lines.
McNamara, T., Shaaban, S., & Hudson, S. (2013). Simulation of unbalanced buffer allocation in unreliable unpaced production lines. *International Journal of Production Research, 51*(6), 1922-1936. doi:10.1080/00207543.2012.720726
McNamara, T., Shaaban, S., & Hudson, S. (2016). Fifty years of the bowl phenomenon. *Journal of Manufacturing Systems, 41*, 1-7. doi:10.1016/j.jmsy.2016.07.003
Miyake, D. I. (1999). Matching the promotion of total quality control and total productive maintenance: An emerging pattern for the nurturing of well-balanced manufacturers. *Total Quality Management, 10*(2), 243-269. doi:10.1080/0954412997983
Muchiri, P., & Pintelon, L. (2008). Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. *International Journal of Production Research, 46*(13), 3517-3535. doi:10.1080/00207540601142645
Nakajima, S. (1988). Introduction to TPM: total productive maintenance.(Translation). *Productivity Press, Inc., 1988*, 129.
Ng, A. H. C., Shaaban, S., & Bernedixen, J. (2017). Studying unbalanced workload and buffer allocation of production systems using multi-objective optimisation. *International Journal of Production Research, 55*(24), 7435-7451. doi:10.1080/00207543.2017.1362121
Nigel Slack, A. B.-J., Robert Johnston. (2016). Operations management.
Öner-Közen, M., Minner, S., & Steinthaler, F. (2017). Efficiency of paced and unpaced assembly lines under consideration of worker variability – A simulation study. *Computers & Industrial Engineering, 111*, 516-526. doi:https://doi.org/10.1016/j.cie.2017.03.030
Rao, N. P. (1976). A generalization of the 'bowl phenomenon' in series production systems. *International Journal of Production Research, 14*(4), 437-443. doi:10.1080/00207547608956617
Raouf, A. (1994). Improving capital productivity through maintenance. *International Journal of Operations & Production Management*.
Robinson, S. (2006). *Conceptual modeling for simulation: issues and research requirements.* Paper presented at the Proceedings of the 2006 winter simulation conference.
Rødseth, H., Strandhagen, J. O., & Schjølberg, P. (2015). *Key performance indicators for integrating maintenance management and manufacturing planning and control.* Paper presented at the IFIP International Conference on Advances in Production Management Systems.
Romero-Silva, R., Marsillac, E., Shaaban, S., & Hurtado-Hernández, M. (2019). Serial production line performance under random variation: Dealing with the 'Law of Variability'. *Journal of Manufacturing Systems, 50*, 278-289. doi:10.1016/j.jmsy.2019.01.005
Schmenner, R. W., & Swink, M. L. (1998). On theory in operations management. *Journal of Operations Management, 17*(1), 97-113.
Shaaban, S., McNamara, T., & Hudson, S. (2014). Mean time imbalance effects on unreliable unpaced serial flow lines. *Journal of Manufacturing Systems, 33*(3), 357-365. doi:https://doi.org/10.1016/j.jmsy.2014.02.006
Şimşit, Z. T., Günay, N. S., & Vayvay, Ö. (2014). Theory of Constraints: A Literature Review. *Procedia - Social and Behavioral Sciences, 150*, 930-936. doi:https://doi.org/10.1016/j.sbspro.2014.09.104
Slack, N., Brandon-Jones, A., & Johnson, R. (2016). Likelihood of failure. In *Operation Management* (pp. 624-629). Harlow, United Kingdom: Pearson education limited.
Slack, N., Brandon-Jones, A., & Johnston, R. (2016). *Operations Management*: Pearson Education Australia.

Smunt, T. L., & Perkins, W. C. (1985). Stochastic unpaced line design: Review and further experimental results. *Journal of Operations Management, 5*(3), 351-373. doi:10.1016/0272-6963(85)90019-1

Thürer, M., Stevenson, M., Silva, C., & Qu, T. (2017). Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation. *International Journal of Production Economics, 188*, 116-127. doi:https://doi.org/10.1016/j.ijpe.2017.03.025

van der Zee, D.-J. (2019). Model simplification in manufacturing simulation – Review and framework. *Computers & Industrial Engineering, 127*, 1056-1067. doi:https://doi.org/10.1016/j.cie.2018.11.038

Venkatesh, J. (2007). An introduction to total productive maintenance (TPM). *The plant maintenance resource center*, 3-20.

Venkatesh, J. (2007). An introduction to total productive maintenance (TPM). *The plant maintenance resource center*, 3-20.

Williamson, R. M. (2006). Using overall equipment effectiveness: the metric and the measures. *Strategic Work System, Inc*, 1-6.

Appendix

Appendix A (bowl model)

Appendix A till E shows the input data for the workload models experiments. The first table of each appendix shows the input data for the experiments, which takes the pasteuriser as the bottleneck of the line. The second table shows the input data for the CPL machine as the bottleneck of the line, and the third table presents the input data for the case packers as the bottleneck of the line. Appendix C shows the input data for the bowl model, Appendix D shows the peak model input data, Appendix E shows the sawtooth model input data, Appendix F shows the reverse sawtooth input data, and lastly, Appendix G shows the levelled model input data.

Machine	Subtype	Pasteuriser 5% step increase	Pasteuriser 10% step increase	Pasteuriser 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Machine	Subtype	CPL 5% step increase	CPL 10% step increase	CPL 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			

	522
Case erector	521
	522
Interior machine	521
	522
Case packer	521
	522
Case closer	521
	522
Palletiser	521
	522
Foiling machine	520
Pallet sticker machine	520

Machine	Subtype	Case packer 5% step increase	Case packer 10% step increase	Case packer 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Appendix B (Peak model)

Machine	Subtype	Pasteuriser 5% step increase	Pasteuriser 10% step increase	Pasteuriser 15% step increase
Defoiling machine	520			

Depalletizer	520
Filling machine	521
	522
Pasteuriser	520
CPL	521
	522
Case erector	521
	522
Interior machine	521
	522
Case packer	521
	522
Case closer	521
	522
Palletiser	521
	522
Foiling machine	520
Pallet sticker machine	520

Machine	Subtype	CPL 5% step increase	CPL 10% step increase	CPL 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Machine	Subtype	Case packer 5% step increase	Case packer 10% step increase	Case packer 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Appendix C (Sawtooth model)

Machine	Subtype	Pasteuriser 5% step increase	Pasteuriser 10% step increase	Pasteuriser 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			

	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Machine	Subtype	CPL 5% step increase	CPL 10% step increase	CPL 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Machine	Subtype	Case packer 5% step increase	Case packer 10% step increase	Case packer 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			

	522
Palletiser	521
	522
Foiling machine	520
Pallet sticker machine	520

Appendix D (reverse sawtooth model)

Machine	Subtype	Pasteuriser 5% step increase	Pasteuriser 10% step increase	Pasteuriser 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Machine	Subtype	CPL 5% step increase	CPL 10% step increase	CPL 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			

Case packer	521	
	522	
Case closer	521	
	522	
Palletiser	521	
	522	
Foiling machine	520	
Pallet sticker machine	520	

Machine	Subtype	Case packer 5% step increase	Case packer 10% step increase	Case packer 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

Appendix E (levelled model)

Machine	Subtype	Pasteuriser 5% step increase	Pasteuriser 10% step increase	Pasteuriser 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			

	522
Case packer	521
	522
Case closer	521
	522
Palletiser	521
	522
Foiling machine	520
Pallet sticker machine	520

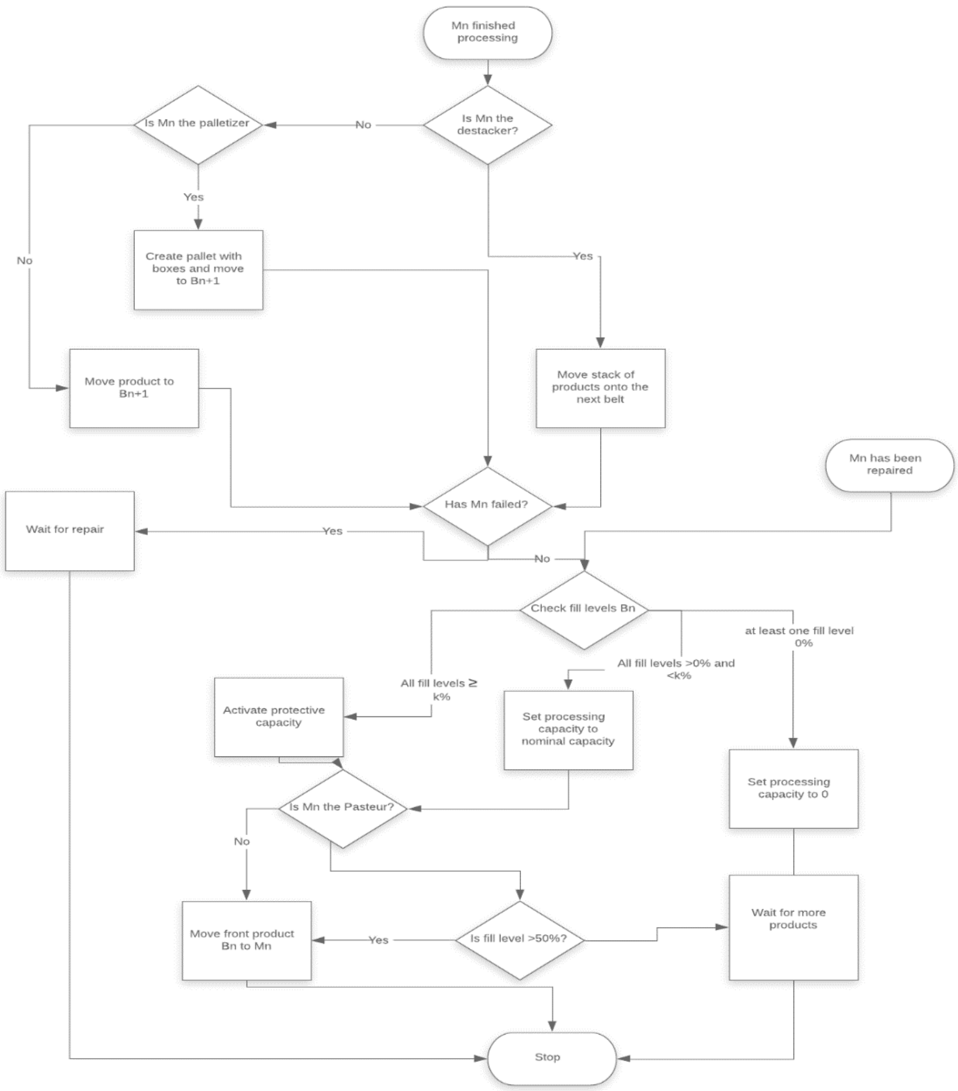
Machine	Subtype	CPL 5% step increase	CPL 10% step increase	CPL 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			
	522			
Interior machine	521			
	522			
Case packer	521			
	522			
Case closer	521			
	522			
Palletiser	521			
	522			
Foiling machine	520			
Pallet sticker machine	520			

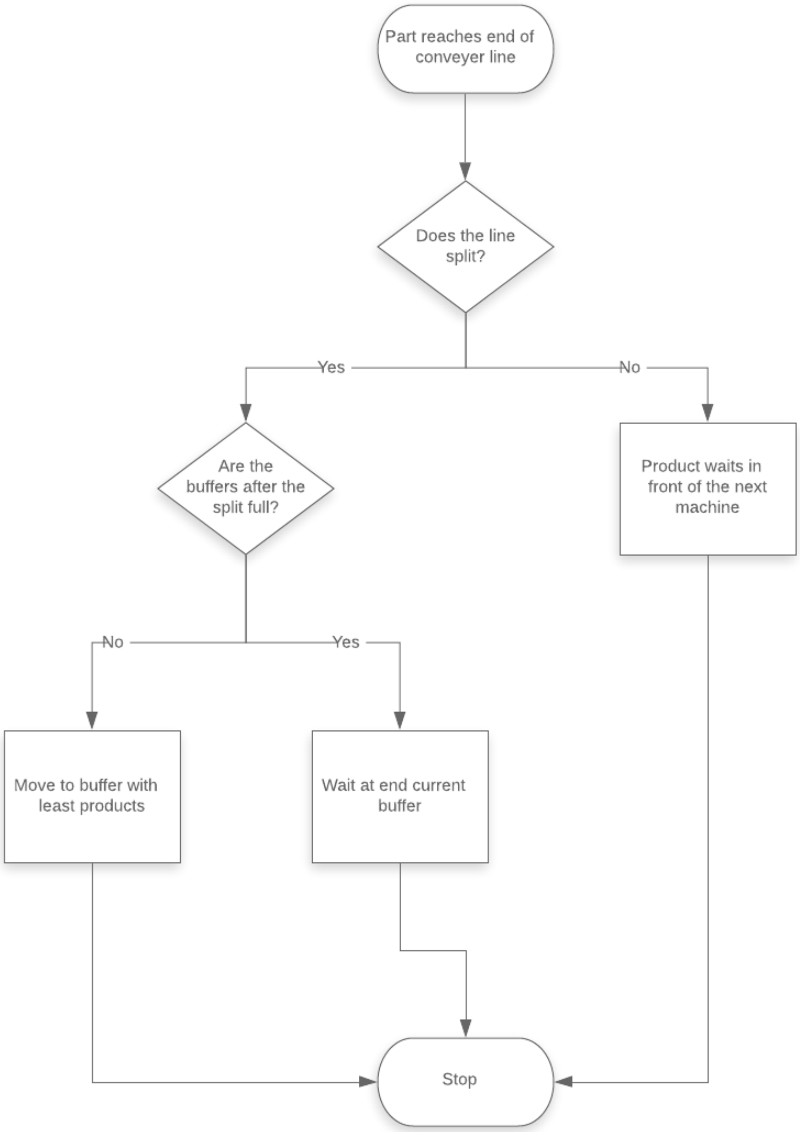
Machine	Subtype	Case packer 5% step increase	Case packer 10% step increase	Case packer 15% step increase
Defoiling machine	520			
Depalletizer	520			
Filling machine	521			
	522			
Pasteuriser	520			
CPL	521			
	522			
Case erector	521			

	522
Interior machine	521
	522
Case packer	521
	522
Case closer	521
	522
Palletiser	521
	522
Foiling machine	520
Pallet sticker machine	520

Appendix F Logic flow for event control

As explained in the introduction of this chapter, the simulation models simulate the events that happen over time. This appendix shows the possible events that can happen and the logic flow that determines the actions that flow out the events.





Appendix G Input data specific buffer experiments

Extra buffer in front of pasteuriser:

From	To	No extra buffer	10% more buffer	20% more buffer	30% more buffer
Filler 521	split				
Filler 522	split				
Split	Pasteuriser				

Extra buffer in front of CPL:

From	To	No extra buffer	10% more buffer	20% more buffer	30% more buffer
Pasteuriser	Split				
Split	CPL1				
Split	CPL2				

Extra buffer in front of case packers:

From	To	No extra buffer	10% more buffer	20% more buffer	30% more buffer
CPL1	Join				
CPL2	Join				
Join	Split				
Split	Case Packer 1				
Split	Case Packer 2				