Enhancing the productivity of a one-way bottling and packaging production line

A case study at Heineken Zoeterwoude

I. de Vries

TU Delft

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Enhancing the productivity of a one-way bottling and packaging production line

A case study at Heineken Zoeterwoude

Master Thesis

By

Ismay de Vries

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Thesis committee:	Prof. dr. R.R. Negenborn	TU Delft, Chair, 3mE
	Ir. M.B. Duinkerken	TU Delft, 1st Supervisor, 3mE
	Ir. M.W. Ludema	TU Delft, 2nd Supervisor, TPM
	E. Kögeler & M.T. van Velsen	External Supervisors Heineken

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Preface

This master thesis is the final step towards graduating from the Delft University of Technology with the master of Construction Management and Engineering at the faculty of Civil Engineering. The aim of this thesis is to research ways in which the productivity of production lines can be increased. In this thesis the focus is on one-way bottling and packaging production lines. This research is conducted in association with the packaging department of the Heineken brewery located in Zoeterwoude.

In this chapter I would like to take a moment to thank the people who helped me deliver the thesis that is in front of you. First of all, I want to thank my graduation committee for their help, feedback and guidance during the process of delivering this thesis. I would like to thank Rudy Negenborn for his critical feedback during the meetings from which I learned to also pay attention to the details. I would like to thank Mark Duinkerken for our regular meetings, helping me set a direction for the research and his feedback with regard to creating a solid model. I would like to thank Marcel Ludema for his feedback during the process from which I learned that also the social aspects are not to be forgotten.

Secondly I would like to thank all the people from Heineken who helped me with delivering this thesis. When I started with my internship at Heineken the direction for the thesis needed to be set. For this I got help from different people which got me to this final thesis. I would like to thank Eric Kögeler for his regular meetings with me from which I was able to keep track of my process and discuss which steps needed to be taken. I would also like to thank all the team leaders of the area. Whenever things were unclear to me I could ask for your help. Furthermore I would like to thank the operators of the area for providing me with the needed information about the production line, helping me with performing measurements and always being in for a laugh or a chat.

Next, I would like to thank my family and friends. To my parents I would like to say how grateful I am for always having your support on the decisions I have made during my studies. You never second guessed the decisions I made and kept believing in me. Quirine, thank you for always being there for me whenever I needed someone to chat to over the phone. Thanks to all my friends for always supporting me whenever I felt like I did not know which direction to go and convinced me to keep going. Last but not least, thank you Hugo, for putting up with me whenever I felt down, you could always make me feel confident again.

My time of studying in Delft has come to an end. I am very grateful for the time I have spent at the university, the opportunities I got studying here and the friends I have made during this period. Now it is time to move on to the next period in my life. I am very much looking forward to all the challenges my future career will bring.

Ismay de Vries
Delft, December 2019

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Summary

The productivity of manufacturing companies is under a lot of pressure as a result of the increasing amount of competitors due to globalisation and the growing use of flexible systems which are trying to perfectly meet the demand of the market (Mourtzis, 2016). For these reasons, manufacturing companies are constantly trying to produce good quality products at a competitive price as fast as possible. This means that different ways need to be established for manufacturing companies to increase their productivity. One of the most occurring problems with regard to productivity of production lines can be seen in the fact that a lot of short stoppages occur. These stoppages influence the machines surrounding them by making these machines go idle.

Based on the previous context, the problem statement this thesis focusses on is the fact that the total productivity of production lines is limited due to several losses. Short stoppages and idling are usually the losses which influence the productivity the most, in means of the total throughput of the production lines (Ljungberg, 1998). This is caused by the fact that a production line consists of several individual machines that are connected with each other. When one machine experiences a failure, it will impact other machines and thus the whole system. This is especially the case when the bottleneck machine is affected by a failure. The bottleneck machine is the machine in the system which generates the lowest throughput and is thus very determinant for the output of the whole system. This problem is influenced by the amount of buffer capacity that is placed in between the machines, the speed at which the machines can process material and the reliability of the machines. However, the exact relationship between these factors and in which ways they influence each other is not investigated extensively (Patti & Watson, 2010). Heineken, the second biggest beer brewing company in the world, is facing problems with regard to the productivity of some of their production lines (Heineken,2019). Especially production line 52 at the brewery located in Zoeterwoude is experiencing a lot of productivity loss due to these stoppages, which cause blockage and starvation on other machines. For that reason Heineken is looking for a way in which the productivity of this production line can be increased.

The goal of this thesis is to investigate how production companies can limit these problems with regard to the losses caused by short stoppages and in that way increase the productivity of their production lines. In this research it is chosen to focus on a certain kind of production line which is used for bottling and packaging of one-way beer bottles. This has been chosen since these kind of production lines can often be seen in the beer industry (Heineken, 2019) (Donoghue, Jackson, Koop, & Heuven, 2012). To do so, the following research question is established:

"What are the root causes for a loss of productivity in one-way bottling and packaging production lines and how can they be decreased?"

To answer this question, different sub-questions are derived. The first step in answering this question is to establish a theoretical framework in which the research could take place. To do so, available literature and information from the field of practice have been used. From these sources it could be concluded that different losses cause a decrease of the performance; set-up and adjustment losses, breakdowns losses, minor stops and idling losses and rejection and rework losses. From these losses, the minor stoppages and idling usually cause the most loss of performance. The amount of loss is dependent on the reliability of the machines which can be defined with the frequency (mean time between failures) and duration (mean time to repair) of the stoppages on the machines. The effect the reliability of the machines has on the total productivity of a production line is dependent on the amount of buffer capacity and the processing capacity of the machines. These can be translated to the buffer time and recovery time of the system. The buffer time is the time it takes before a stoppage at one machine influences another machine. The recovery time is the time it takes for a buffer to recover to its nominal fill level after a stoppage. Both these times have a high impact on the productivity of the system (Sorgatz & Voigt, 2013). To increase the performance of the system different approaches exist with regard to balancing or un-balancing production lines. These approaches are the Theory of Constraints, Kanban systems, the bowl phenomenon and different allocations of protective capacity along a production line. To measure the productivity of a production line different Key

Performance Indicators (KPI's) can be used, of which the Overall Equipment Efficiency (OEE) is the most commonly used (Aman, Ezzine, Fattah, Lachhab, & Moussami, 2017). This thesis focusses on the performance part of this KPI. This performance can be calculated by dividing the actual throughput of the system by the amount of throughput that could have been produced in the time that was available for production (Pintelon & Muchiri, 2008).

Once the theoretical framework has been established, these approaches are compared to each other and applied on a generic model of a one-way bottling and packaging process. To do so, a simulation model of this generic process is established. Different alternatives with regard to protective capacity, the amount of buffer capacity and reliability are applied to this model. For the shape of protective capacity five different shapes are considered: the constant, peak, bowl, sawtooth and reversed sawtooth shape. With regard to the amount of buffer capacity it has been tested what the effect is of adding larger or smaller buffers in between the machines or at one particular place in the system. All these alternatives have been tested against different reliability configurations.

It is concluded that a production line which has some sort of protective capacity in place will always perform significantly better compared to a production line without protective capacity in place. Out of the five different shapes that have been tested, the constant, peak and sawtooth shape outperform the reversed sawtooth and bowl shape in most cases. Adding more protective capacity will significantly increase the performance of the system, however quality losses caused by wear and tear of the machines need to be considered. With regard to buffer capacity it can be stated that adding more capacity in between the machines significantly improves the performance. However adding a lot of buffer capacity is not always possible or desirable. For that reason it has been tested where in the system it is most productive to place an extra amount of buffer capacity. In the case that all machines have an equal reliability, it is best to place the extra amount of buffer capacity directly after the bottleneck machine. However, when the most unreliable machine is located upstream of the bottleneck machine, the extra amount of buffer capacity can best be placed directly in front of the bottleneck machine. Whenever a machine downstream is less reliable, it is however best to place the extra amount of buffer capacity directly after the bottleneck machine or directly in front of the most unreliable machine. With regard to when the protective capacity needs to be activated there is no preference when medium sized buffers are located in between the machines. However, when larger buffers are placed in between the machines it is best to activate the protective capacity earlier when buffers are starting to get either fuller or emptier.

To apply these improvement alternatives in the field of practice, a case study has been performed. This case study is conducted at production line 52 of the Heineken brewery located in Zoeterwoude in the Netherlands. This line is chosen, since the performance of this line is below what is desirable. To perform the case study, first a data analysis is performed to analyse what the current situation is and which areas are the most critical. In this analysis the processing times and reliabilities of the machines have been investigated together with the properties with regard to buffer capacity and buffer control, which are translated into buffer time and recovery time of the buffers. From this analysis it followed that especially the area around the bottleneck machine, the pasteurizer, and the area in which the bottles are packaged in boxes are critical to the performance of the system. To investigate how the performance could be improved, a simulation model of the production line has been made.

From this model it followed that the implementation of the sawtooth shape, the constant shape or the peak shape at production line 52 will give a significant higher performance compared to the current performance and the implementation of the reversed sawtooth shape or the bowl shape. Besides that, the sawtooth shape gave the significant best performance of all five shapes. However, implementing this shape at production line 52 is not possible due to the technical limitations of the system. For this reason it is checked if significant performance improvement can be reached when the sawtooth shape is implemented within this limits. This has proven to give a significant better performance compared to the current one. The performance of production line 52 can be significantly improved by making sure all the mean time between failures and mean time to repair of all machines meet the target values that are set based on respectively the recovery time of the buffers and the buffer time. Furthermore, it followed from these experiments that adding buffer capacity either before the packaging machine, one of the most unreliable machines, or after the pasteurizer, the bottleneck machine, will increase the performance of the system.

Finally, some recommendations are given with regard to future scientific research, the field of practice, Heineken and production line 52. First of all, with regard to future research it is stated that different shapes of protective capacity and different reliability configurations might be interesting to investigate. Furthermore, also investigating the effect of having the bottleneck located at a different position might be interesting. Secondly, based on the results of all the experiments, some recommendations for the field of practice can be given. For the field of practice it is recommended to investigate what the reliabilities of the machines will be when investing in a new production line. Based on these reliabilities the placement of buffers and the use of protective capacity should be determined beforehand. During operation it is recommended for the field of practice to continuously keep track of the mean time between failures and the mean time to repair in relationship with the recovery time and the buffer time. If these values are not met, proper maintenance actions should be determined. For Heineken also some recommendations are given. It is first of all recommended to rethink the idea behind the "*V-shape*" and try to implement different configurations of protective capacity at the production lines, based on the reliability of the machines. Furthermore, a more structured data collection of the machines is advised. For specifically production line 52 some recommendations are given as well. For this production line it is recommended to implement the sawtooth shape within the technical limitations of the system. If this is done, it is advised to continuously keep track of the reliability of the machines. This can be done with a file that compares the reliability with the buffer time and recovery time. Furthermore, when maintenance action is required it is advised for production line 52 to do this with the use of the diagram that is created in this thesis. In this diagram it can be seen which causes of failure are the most common for each machine. Based on this diagram this causes should be mitigated or reduced.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

DBR .... *Drum Buffer Rope*
DES .... *Discrete Event Simulation*
JIT .... *Just in Time*
KPI .... Key Performance Indicator
MES .... *Manufacturing Execution System*
MST .... *Mean Stoppage Time*
MTBA .... *Mean Time Between Assists*
MTBF .... *Mean Time Between Failures*
MTTR .... *Mean Time To Repair*
OEE .... *Operational Efficiency Effectiveness*
PLC .... *Programmable Logic Controller*
TPM .... *Total Productive Maintenance*
WIP .... *Work in-process*

1 Introduction

This chapter firstly introduces the context in which the research is conducted by discussing the current state of the sector and explaining the currently occurring problems. In the second paragraph the problem this thesis focusses on is elaborated, as well as the objective of the research. In addition to that the questions which follow from the problem, the relevance of the research conducted in this thesis and the scope of the research are discussed in the second paragraph. The third paragraph elaborates which methods are used to answer the sub-questions. Finally, an outline of the thesis is given in the fourth paragraph.

1.1 Context of the Research

The productivity of manufacturing companies is under a lot of pressure. This is the result of the increasing amount of competitors caused by globalisation. Furthermore, the growing use of flexible systems which are trying to perfectly meet the demand of the market also increases this pressure (Mourtzis, 2016). For these reasons, manufacturing companies are constantly trying to produce good quality products at a competitive price as fast as possible.

Achieving the desired productivity implies that a company should have a high availability of equipment. This can be achieved by having as little failure as possible, which can be reached through higher equipment reliability and maintainability (Sharma, Shudhanshu, & Bhardwaj, 2012). For this reason the use of an effective strategy which enhances and continuously improves the performance of the production line is becoming increasingly important for manufacturing companies. To do so, short stoppages and idling are of importance, since this influences the productivity of production lines by limiting the total throughput. A stoppage can be either be categorised as short or long. A short stoppage has a lower chance of stopping the whole production line compared to larger stoppages and breakdowns. A short stoppages at one machine can make other machines go idle. Idling is caused by stoppages in means of blockage and starvation. Starvation occurs when a stoppage on one machine causes a lack of material to process for another machine. Blockage occurs when due to a stoppage on one machine another machine has no place to put its processed material. Starvation and blockage especially need to be avoided on the bottleneck machine of a production line. This is the case since when this happens it immediately effects the total throughput of the system.

This thesis focusses on a one-way bottling and packaging production line. The steps that are taken in a typical non-returnable one-way bottling and packaging process, can be seen in Figure 1.1. Firstly the empty bottles arrive on a pallet and need to be removed from this pallet. After that they are filled with beer and pasteurized to make sure they have the proper expiration date. Subsequently a label is put on the bottles. Finally, the bottles are packaged in the right packaging material and put on a pallet, this prepares them to be exported (Priest & Stewart, 2006) (Basan, Coccola, & Mendez, 2014).

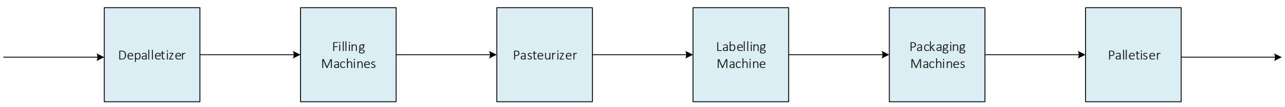

Figure 1.1: Production steps of a non-returnable bottling and packaging process

Heineken, the second biggest beer brewing company in the world, is also facing problems with regard to the productivity of some of their production lines which is caused due to these stoppages. Since Heineken wants to increase their productivity they are looking for ways to mitigate or reduce the effects and causes of these short stoppages. By doing so, the throughput of their production lines can be increased. Heineken's biggest brewery in the Netherlands is located in Zoeterwoude. One of their newest production lines is production line 52. This is a bottling and packaging line in which beer is prepared to be exported in bottles which are packaged in boxes. This means that the bottles that are being used are non-returnable. Production line 52 is relativity new, as it is being operated since mid-2017. However, this line is not operating at the expected productivity level and therefore needs improvement. Especially the bottleneck machine of this production line, the pasteurizer, is experiencing a lot of blockage and starvation which is caused by short stoppages on other machines. When the productivity of the bottleneck machine is below its capabilities this means that the total throughput of the line is decreased due to that fact. When a stoppage occurs upstream of the bottleneck machine, the bottleneck machine can get starved as a result of this stoppage. Whenever a stoppage occurs downstream of the bottleneck machine, the bottleneck can eventually get blocked due to this stoppage. This problem is elaborated in more detail in the next paragraph.

1.1.1 Research Problem

Improving the productivity and performance of a production line is important as it increases the throughput and it ensures the orders can be completed in the required time. If a production line is not operating at the expected productivity level, it is usually the result of stoppages and breakdowns. The losses caused by short stoppages and idling, influence the overall productivity usually the most with a loss of productivity of around twenty to thirty percent of the total available production time (Ljungberg, 1998) (Heineken, 2019).

The fact that these losses are high is caused by the effect that one stoppage has on the total production line, which can be very big in integrated machinery systems. A stoppage on one machine can cause a lack of working material on the next machine once the buffer space on the conveyor belt is completely emptied and make that machine go idle. The opposite is possible as well since once working material arrives at a full buffer it is not possible to continue to the next machine in the system (Ljungberg, 1998). The importance of minimizing these stoppages is mainly to avoid the bottleneck machine of the production line from being either blocked or starved. The bottleneck machine is the machine in the line with the lowest output and thus determent for the total throughput of the production line. It is desirable for this machine to work as efficiently as possible to maximise the total output of the production line. To do so, extra attention needs to be paid to minimizing the effects and causes of stoppages.

Figure 1.2 displays what happens when stoppages occur at a production line. Due to a stoppage at machine 2, the amount of used buffer capacity between machine 1 and machine 2 is increasing. The buffer level moves from point A to point B in this example. This could eventually lead to a blockage on machine 1. The opposite occurs at the buffer between machine 2 and machine 3. This buffer is slowly emptying and might eventually cause machine 3 to become starved. When this happens, the buffer between machine 3 and machine 4 could become below the nominal fill level of the buffer. The likelihood of occurrence is determined by the processing capacities of the machines.

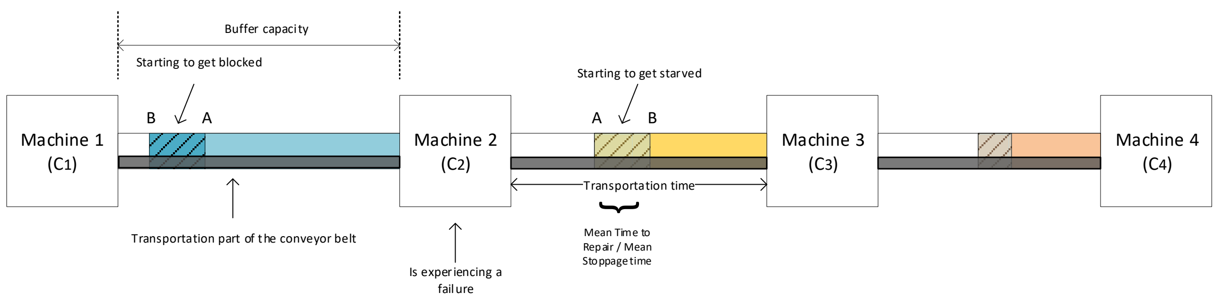

Figure 1.2: Effects of a stoppage on a production line

After a few minutes the stoppage is usually solved and the machines start producing again. When production commences, the buffers are fuller or emptier than they normally are. To compensate this, machines start to work at a faster or slower speed to recover to the nominal fill level of the conveyor belt. How and when this happens determines how fast a buffer can recover from the occurrence of a stoppage. Furthermore, when the next stoppage occurs it is important for the buffer to be at the nominal fill level again. Otherwise the machines will even sooner be blocked or starved. How often this happens depends on the properties of the system, especially the amount of buffer capacity that needs to be replenished or depleted and the speed at which the machines process. The faster a machine can process the material, the sooner the buffer is recovered. The larger the buffer capacity is, the less impact a stoppage has on other machines (Sorgatz & Voigt, 2013). Commonly used conveyor belts in bottling plants can usually cope with short stoppages lasting between 60 and 120 seconds. However stoppages exist which last longer than this time period (Sorgatz & Voigt, 2013) (Bernhand, 2000). This means that the buffers which are generally present in bottling plants are not able to prevent all stoppages from influencing other machines. Even though the duration of these stoppages might be relatively low, the frequency can be very high (Heineken, 2019) (de Smet, Gelders, & Pintelon, 1997). Due to this high frequency the chance of the buffer reaching its nominal fill level before the next stoppage occurs is lower.

The bottleneck machine defines the total output of the system. However, if other machines are experiencing stoppages, this bottleneck can become starved or blocked, which causes the total throughput of the production line to decrease. For this reason it is important to look at the performance of all the other machines in the production line as well, to make sure that stops on these machines have as little influence on the total throughput of the production line as possible. Besides the negative effect stoppages have on the production time and thus on the productivity of the production line, the often stopping and starting of machinery can also cause wear and tear on the machines. This influences the failure probability of those machines, creating an even higher chance of failure of the machines.

1.1.2 Research Objective

The objective of the research is derived from the above mentioned problem. First of all, this is to determine what the root causes are for a loss of productivity in production lines, especially with the focus on one-way bottling and packaging production lines. Once these causes have been determined, the second objective is to determine ways in which this loss can be decreased. This is done by analysing these before determined factors and determining how these can be altered to improve the productivity of a production line.

1.1.3 Research Questions

Following from the above stated objective, the main research question has been drawn up:

“What are the root causes for a loss of productivity in one-way bottling and packaging production lines and how can this loss be decreased?”

To be able to give an answer to this main research question, multiple sub-questions need to be answered. These questions are answered following from sub-question 1 to sub-question 5 to get the appropriate answer for the main research question. This contains the following sub-questions:

1 *“Which factors influence the productivity of a production line?”*

2 *“Which of these factors can be altered to improve the overall productivity of a production line?”*

3 *“What advice can be given to improve the overall productivity of a one-way bottling and packaging production line?”*

4 *“How do the above described factors act in the field of practice as can be seen at production line 52 of Heineken?”*

5 *“What advice can be given to Heineken with regard to improving the productivity of production line 52?*

The methods that are used to answer these questions are elaborated in the seventh paragraph, which explains the research methodology of this thesis.

1.1.4 Relevance of the Research and Research Gap

Even though the importance of the focus on short stoppages is noted in the literature, the attention to these losses is not very extensive, both in practice and in theory. In a lot of occasions the short and chronic stoppages are seen as something that is normal and there is no awareness of the impact these stoppages have on the total productivity (Ljungberg, 1998). The operators on the production line regard the solving of these minor stoppages as just a part of their job and not something that needs to be prevented in the future to improve the overall productivity of the system (Heineken, 2019). From this it can be concluded that there is a need to further investigate ways in which the loss caused by these stoppages can be reduced or mitigated, since these stoppages are responsible for around twenty to thirty percent loss of production due to the idling on other machines. Shirose (1996) as well says it is important to pay attention to the short stoppages as the accumulated effects of these can be very big (Sharma, Shudhanshu, & Bhardwaj, 2012) (Shirose, 1996). The same holds for Suehiro (1987), who sees the elimination of these short stoppages as one of the highest priorities for continuous improvement (Suehiro, 1987). Benjamin et al. note in their research that short stoppages usually have been accepted as an unavoidable waste and that it has never been attempted to reduce or eliminate with the method they investigated in their research (Benjamin, Murugaiah, & Marathamuthu, 2013). From this it can be stated that it is of high importance for manufacturing companies to focus on decreasing the occurrence of these stoppages and reducing the effects to improve the performance of the system and thus their productivity and efficiency.

Consequently, it can be stated that a research gap exists in the literature concerning short stoppages. Nonetheless, there is a lot of literature about improving the overall productivity of production lines (Aman, Ezzine, Fattah, Lachhab, & Moussami, 2017) (Hudson, Shaaban, & McNamara, 2015) (Takahashni, Morikawa, & Chen, 2007). However, this literature is often contradictory to each other. Therefore, research is necessary which combines the different approaches in the literature. This thesis will do so by comparing and combing these different approaches in order to draw general conclusions regarding the improvement of the productivity of one-way bottling and packaging production lines.

Looking at other graduation theses this subject has been addressed a couple of times in studies with regard to production lines of breweries. First of all the thesis of Emily Verwaal "*Increasing efficiency of a production line by using protective capacity*" at the Delft University of Technology (Verwaal, 2018). In her thesis she performs a case study at Heineken Den Bosch in which she investigates how changes in the amount of protective capacity, the extra capacity of machines compared to the bottleneck, can change the efficiency of a production line. She has researched this by making a simulation model based on the failure rates of the most unreliable machines at one of the production lines of Heineken at the packaging department in Den Bosch. She concludes that changing the speed of the non-constraint machines, meaning all the machines except the bottleneck, probably influences the efficiency of a production line. Besides, she also looked at in which way the protective capacity must be divided to utilize it in the best way. A small preference to a shape of protective capacity that increases towards the bottleneck is given, but this could be different for other production lines with different properties. Peter Scholten researched this subject as well in his thesis "*Efficiency analysis and improvement at Grolsch*" (Scholten, 2016). In his research he focused on the blockage and starvation of the bottleneck machine of a canning line at the Grolsch brewery. He made a simulation model in which he tested to change the fill level of the buffer on which the machine speeds change.

The research gap within these theses can be seen in the fact that the research of Verwaal focused mostly on the non-bottleneck machine and the research of Scholten on the bottleneck machine. However, an integral study of the whole system is important since all the machines that are part of the system can have a big influence on each other. Verwaal only incorporated one failure rate in all the machines, which is not realistic since some machines can be a lot less reliable than other machines, for this reason machines with different failure rates need to be investigated in more detail. Besides, Verwaal did not focus on the recovery time of the buffers, whereas Scholten did. This could be of very high importance since when the buffer is fuller or emptier than the nominal fill level, another machine more easily gets starved or blocked. This process needs to be investigated in more detail. The best way this could be done is by looking at a real life problem and try to draw a general conclusion for other production lines from this problem.

The relevance of this thesis within the framework of the master of *Construction Management & Engineering* is elaborated in Appendix L**Fout! Verwijzingsbron niet gevonden.**. In this appendix it is explained that *Construction Management* can also be seen as the management of something that once has been constructed and is now in operation. In this thesis this has been applied to production lines, which are the assets that need to be managed for a manufacturing plant, in the case study of this thesis for Heineken. In this thesis the structure will however not be a large infrastructure or building, but a production line which is part of a manufacturing plant.

1.1.5 Scope of the Research

As the direction and relevance of this thesis is clear, it is furthermore necessary to set the boundaries in which the research takes place. This thesis mainly focusses on the short stoppages that occur on production lines. This choice is made because of the different nature of shorter stoppages and larger breakdowns. Whereas a short stoppage is usually an error in the process or equipment and can quickly be solved by adjusting or resetting a machine, a breakdown has a more technical nature. A breakdown can last for over an hour, or even over a day and the causes of the breakdown needs to be analysed in detail before a solution for the failure can be found. Due to these breakdowns the whole production line often comes to a stop. This means that the only way to avoid these breakdowns is to analyse the causes of the failure and to prevent them from happening in the future. These causes can for example be due to a lack of maintenance or a technical error in the system. A shorter stoppage however, does not cause the whole production line to be stopped, because the error is usually solved before this happens. This is due to the fact that the buffer that is placed between the machines is able to absorb the failure for a certain time period, before it influences other machines. For these reasons, this thesis investigates ways to reduce the causes and effects of these short stoppages, since this can be done by adjusting factors in the system. The nature of these stops is usually a short error that needs to be solved. This could for example be caused by maintenance errors, mistakes in settings or mistakes in the material. The effects can be reduced by preventing machines from becoming idle due to failure on another machine by changing properties of the system. The focus of this research is on finding the best improvement alternatives which are based on these different properties.

Besides that, also focus is paid to a production line with certain theoretical properties. This has been chosen since otherwise it would be too broad to investigate. For this research the choice is made to focus on an asynchronous, un-paced and unreliable production lines with finite buffers. These properties are the properties which are most comparable to production lines in the field of practice and are often discussed in literature (Battini, Persona, & Regattieri, 2009) (Hudson, Shaaban, & McNamara, 2015). The exact meaning of these properties and what it means for the research, is elaborated in the theoretical framework that is given in chapter two. Furthermore, the focus of this thesis is on a production line which performs a one-way bottling and packaging process of a brewery. It studies the bottling process in bottles and not in cans or kegs. For the most part the advices which are given in this thesis are also applicable for other kind of production processes, but since the focus of this thesis is on a one-way bottling and packaging process, the advices are limited by that fact.

Furthermore, this thesis focusses on three different levels which are displayed in Figure 1.3. First of all, the focus is on a general level. This level concerns chapter two and chapter three of the thesis. At this level general advices regarding the improvement of the productivity of one-way bottling and packaging process are given which can be applied to different companies using such a process. The second level that is considered in this thesis is that of Heineken. This level is discussed in a part of the fourth chapter. In this chapter the context of Heineken within the first level is elaborated. At this level advices are given which can be used by Heineken in general. Thirdly, the level of production line 52 is considered. This level concerns part of chapter four and chapter five. In these chapters the production process of line 52 is analysed and advices to improve the productivity of that production line are given.

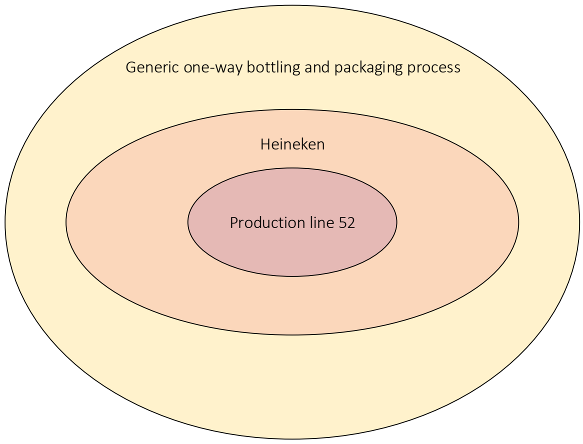

Figure 1.3: Focus levels

1.2 Research Methodology

In this paragraph the research methodology is discussed. A summary of the methodology can be seen in Figure 1.4. The first research questions that were asked in the previous paragraph are answered with the use of a literature study and with information from the field of practice, meaning an empirical study. This has been chosen since both are necessary to get a complete picture of the reality. A literature study gives the current state of the art with relation to the subject of the research and represent the foundation for the research (Webster & Watson, 2002). The limitations of a literature study can however be seen in the fact that a coupling with the field of practice might be missing. For that reason it has been chosen to also perform an empirical study.

An empirical study based on experience of people in the field of practice and observations is necessary to get a good overview of the current state of the art. In this way the practice is tied to the available theory from the literature (Flynn, Sakakibara, Schroeder, Bates, & Flynn, 1990). It has been chosen to combine a literature study with an empirical to study to be able to compare the findings from literature with the findings from practice. In this way a more general overview regarding the problem can be given.

The literature and empirical study together establish a theoretical framework. Following from this theoretical framework it has been chosen to create a generic model in which the found approaches can be tested and compared to each other. A general model has been chosen for the reason that it can give a more generic view regarding the improvement of the productivity of one-way bottling and packaging production lines. Solely using a case study would not be as useful, since it has a smaller applicability. The advantage of a generic model is that different companies and different production lines besides the line studied in a case study can gain insights from this more general study.

When the first questions have been answered, a general concept regarding the improvement of the productivity of production lines has been formed. Following from this general model it has been chosen to perform a case study as well. A case study can be defined as “a research strategy which focuses on understanding the dynamics present within single settings” (Eisenhardt, 1989). Case studies can be both quantitative and qualitative and can be used to accomplish various aims such as providing a description, testing a theory or to generate a theory (Eisenhardt, 1989). A case study studies a bound “case”, meaning for example a process, activity, event, program or multiple individuals (Hancock & Algozzine, 2006). The goal of a case study is to compare the theory with an actual situation from the field of practice. In this way the concepts that are elaborated in the theoretical framework and generic model can be applied to a real situation from the field of practice. This has been chosen because in this way it can be seen how the generic model can be applied to a real life production line.

The following paragraphs elaborate for each sub-question in which way an answer is derived.

1.2.1 Sub-question 1

Sub-question 1 is stated as the following question: *"Which factors influence the productivity of a production line?"*

The occurrence of short stoppages on a production line has a big impact on the overall productivity of a production line. In this question it is investigated which factors play a role in this problem. In this chapter it is firstly investigated what kind of production lines exist and what kind of failures can occur on a production line. Afterwards, the effects of a failure or stoppage on a production line are elaborated. This chapter elaborates on information available from literature study as well on information from the field of practice. Answering this question is the start of creating a theoretical framework in which the research takes place.

1.2.2 Sub-question 2

The following question is the second sub-question that is needed to be answered: *"Which of these factors can be altered to improve the overall productivity of a production line?"*

Once the factors influencing the productivity of a production line have been identified, the question needs to be answered which ways exist to improve the productivity of a production line based on these factors. Different approaches exist with regard to improving the productivity of a production line. These different approaches are elaborated to answer the second sub-question. From these approaches it follows which factors are able to be influenced and which of these factors are able to reduce the effects of these stoppages. Finally, the Key Performance Indicators (KPI's) that are usually used with regard to production line productivity are discussed. Based on the theoretical framework that is set in the first and second question, different improvement alternatives are proposed that could be used to improve the productivity.

1.2.3 Sub-question 3

The third sub-question is the following: *"What advice can be given to improve the overall productivity of a one-way bottling and packaging production line?"*

Once improvement alternatives have been proposed the next step is to test how these alternatives perform compared to each other. This comparison is made based on a generic model of a one-way bottling and packaging process. This generic model is based on the main machines that can be seen in this process. After the model has been created the before found improvement alternatives are applied on this model. This is done with the use of a simulation model created in Simio.

To analyse the performance of a production line and the improvement of those lines, in most academic literature is made use of either analytical models or simulation models. In the book *Production Systems Engineering* by Li and Meerkov (2008) statistical formulas have been developed for production lines with different kind of properties (Li & Meerkov, 2008). Besides, Li et al. (2009) have investigated and summarised different mathematical models that are used for production lines with different properties. However, these analytical models are often too simplistic to represent a real-life situation, because of the assumptions on which they are based (Padhi, Wagner, Niranjan, & Aggarwal, 2013). For this reason, a lot of authors in the literature around this subject chose to perform a simulation study to better represent the situation and its stochastics in reality (Bartkowiak & Pawlewski, 2016) (Basan, Coccola, & Mendez, 2014) (McNamara, Shaaban, & Hudson, 2012) (McNamara, Shaaban, & Hudson, 2012). For the purpose of this thesis a simulation model to analyse and enhance the performance of a production line is more suitable as well. This is the case since a lot of stochastic variables play a role in the problem and changing one of these variables can have impact on multiple other variables. To be able to mimic the real life situation as good as possible, a simulation model is the best choice to investigate this. Discrete Event Simulation (DES) is able to break down each process that is happening into discrete parts, in this way it is easier to analyse different variables and more factors can be considered (Simio, 2019). Simio is one of the available software able to do this kind of simulation, which is used in this thesis. It has been chosen to use Simio since this simulation software is relatively user-friendly compared to other discrete event simulation software. Furthermore, Simio is able to incorporate all the variables that are considered in the problem.

All the different improvement alternatives that followed from the second question are applied on this generic model. This results in an advice with regard to which improvement alternatives perform the best in this generic situation. This means that this question gives a general advice based on the generic model. It states how to improve the productivity of any arbitrary production line, that fills and packages bottles, with the same properties as the line under investigation.

1.2.4 Sub-question 4

The fourth sub-question that needs to be answered is the following: *"How do the above described factors act in the field of practice as can be seen at production line 52 of Heineken?"*

In the first question, the factors that play a role in this research are discussed, followed by a generic model in which it is tested how these factors could be altered. The next step is to investigate how these factors can be applied in the field of practice. This is done based on a case study which is conducted at production line 52 of the Heineken brewery located in Zoeterwoude. To do so, the data that is available from Heineken needs to be analysed. Data from the machines and the performance is collected in the *Manufacturing Execution System* (MES) that is used by Heineken. This system shows for each machine when they are experiencing a failure, are starved, blocked or not producing. The exact number of minutes of stoppages can be found here as well. Some of the data necessary for the research is not available from the available sources. This data needs to be collected through manual measurements on the production line or from information from operators or other employees. This data collection is performed by measuring with a stopwatch, using the counters at the machines and counting boxes on the conveyor belts.

Once this data has been collected, it is clear how the production line of Heineken is currently performing and how the before mentioned factors act in a situation in the field of practice.

1.2.5 Sub-question 5

The fifth sub-question is the following: *"What advice can be given to Heineken with regard to improving the productivity of production line 52?*

Following from the data analysis that has been conducted in the previous question, the next step is to apply the conclusions with regard to the improvement alternatives found in the third question on the case of production line 52 of Heineken. To do so, the simulation model that was created by answering the second question is extended to represent production line 52 of Heineken and the data found in the previous question is the input for the simulation model. The different proposed improvement alternatives are applied on the model. The result of this is an advice for Heineken. In this advice the different possible improvement alternatives that increase the productivity of the production line are elaborated and translated into a implementation plan for Heineken.

1.2.6 Steps of answering the sub-questions

The figure below gives a summary of all the steps necessary to derive to an answer for the sub-questions. The text in blue is the result of each sub-question.

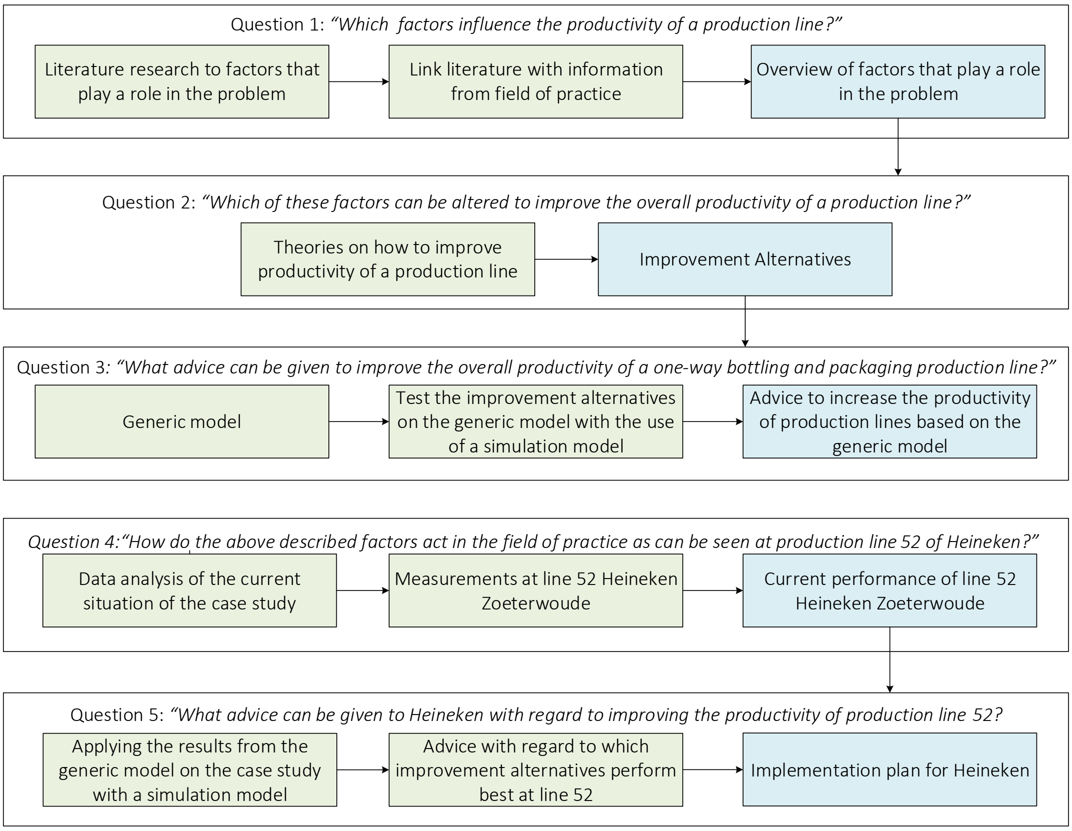

Figure 1.4: Steps of the methodology

1.3 Thesis Outline

The figure below gives an outline of what is discussed in the different chapters of this thesis. This thesis starts with an introduction of the research, followed by the theoretical framework, a generic model, a case study and advices that can be given. Finally a conclusion and final recommendations are given.

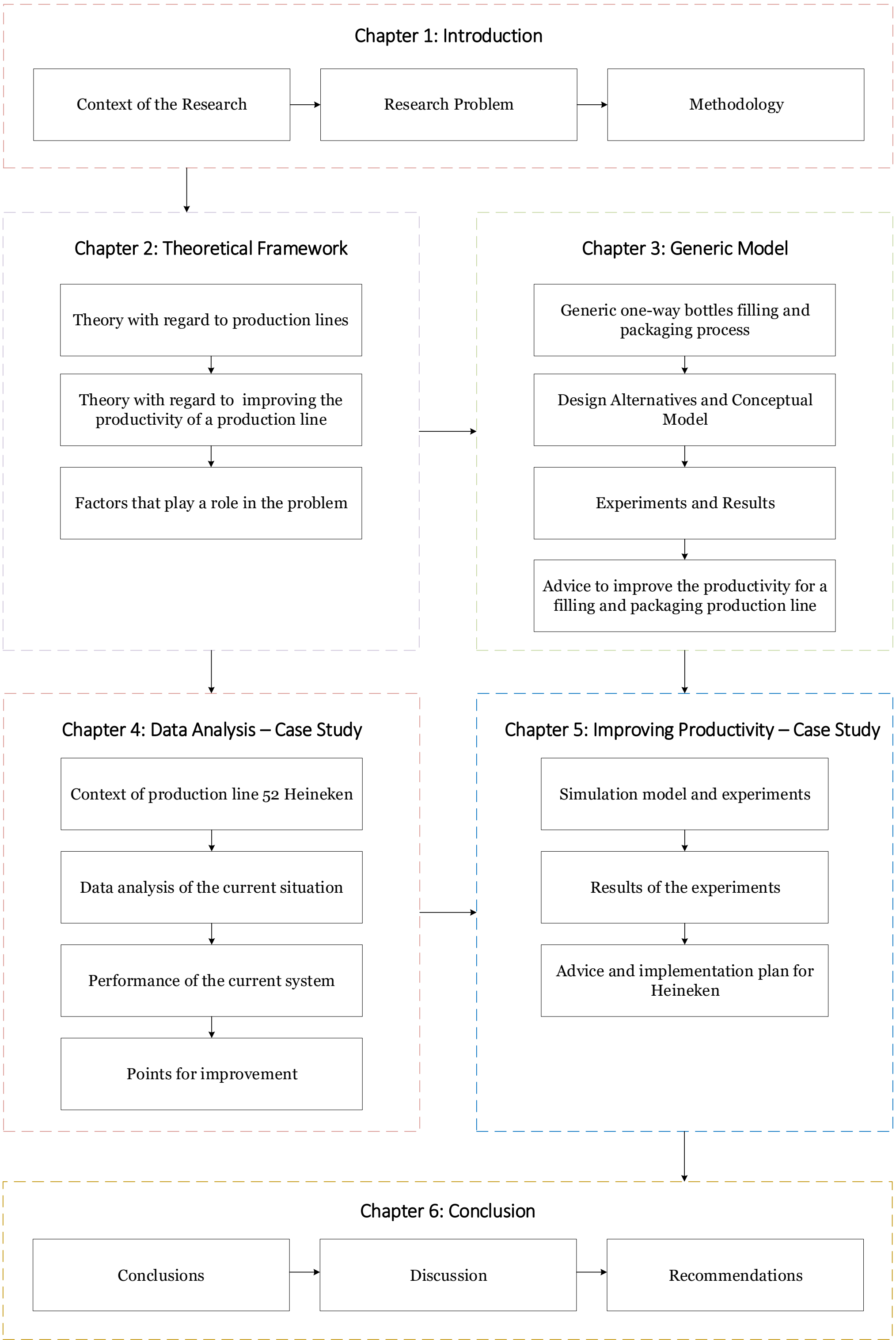

Figure 1.5: Thesis outline

2 Theoretical Framework

In this chapter the theoretical framework in which this research takes place is elaborated. Different theoretical aspects that play a role in the before described problem are elaborated. First of all a general description with regard to the properties of a production line is given in the first paragraph. After that the second paragraph elaborates which maintenance strategies exist with regard to production lines in the manufacturing industry. In the third paragraph the effect downtime has on the availability of a machine or system is explained. This is done by giving a definition of availability and downtime, explaining the different causes of downtime and how the system can cope with downtime. The difference between system and machine availability is addressed in this paragraph as well. In the next paragraph it is elaborated which approaches exist with regard to how a production line can best be organised according to its properties and its downtime behaviour, which can either be balanced or un-balanced. The methodologies and approaches that are discussed are the Theory of Constraints (TOC) and its Drum Buffer Rope (DBR) methodology, the bowl phenomenon, Kanban system and approaches with regard to the allocation of protective capacity along a production line. In the final paragraph it is elaborated in which ways the performance of a production line can be measured and the KPI's which are used in this thesis are elaborated.

2.1 Production Lines

A production line is according to the Cambridge Dictionary defined as:

> *"A line of machines and workers in a factory that a product moves along while it is being built or produced. Each machine or worker performs a particular job that must be finished before the product moves to the next position in the line"* (Cambridge Dictionary, n.d.).

In the available literature a production line is mostly categorised according to the different theoretical properties it has. These different properties are each explained below.

2.1.1 Properties of a production line

The different theoretical properties by which a production line can be categorised are: synchronous and asynchronous, paced and un-paced, finite and infinite buffers and unreliable or reliable machines. All these properties are elaborated below.

Synchronous and asynchronous production lines
In an asynchronous production line a product is moved to the next machine whenever it is finished being processed by the previous machine if there is place for the product (Urban & Chiang, 2016). This means that the parts that are being processed are not being processed simultaneously (Buzacott & Shanthikumar, 1993). Meaning each individual part that goes through the system is processed individually and at different speeds by the machines (Liu, Li, & Chiang, 2012). A synchronous production line means that the timing of the processing is coordinated in such a way that all the machines are processing simultaneously (Urban & Chiang, 2016).

Paced and un-paced production lines
An un-paced production line means that the processing times of the different machine are not constant and can vary over time (Hudson, Shaaban, & McNamara, 2015). This means that the machines which are located along a production line do not produce with the same speed. The machines can be set at different speeds, dependent on different conditions. The changing of these speeds can occur automatically due to certain conditions of the production line or happens due to manual adjustments. When a production line is paced, it means that the processing times of the machines are constant and do not vary over time.

Production lines with infinite or finite buffers

When a production line has infinite buffers it means that the buffers that are located in between the machines are able to absorb all the material that the previously machine has processed and thus the machine that is located before the buffer is never blocked because it does not have place to put its processed material. This is however a theoretical concept and is not possible in a situation in the field of practice. This means that the buffers are finite, the buffers in between the machines have a maximum capacity of products that can be placed on these buffers. The impact of that is that whenever a buffer is full it influences other machines on the production line, by becoming blocked due to no available place on the buffer (Hendricks, 1992). The opposite happens whenever the buffer is completely emptied, which means that the machine has no material to process and becomes starved.

Reliable and unreliable production lines

A reliable production line means that the machines that are part of the production line do not experience failures and thus production on these machines is never stopped due to a failure of the machines. This is however a theoretical concept, in the field of practice every machine experiences failures in its life time. When a production line is defined as unreliable, it means that the machines along this line do experience failures. Meaning that every once in a while a machine stops working. This is comparable to the reality, since a machine can hardly ever be perfect and is also dependent on external influences. When machines are unreliable this adds more variability to the line than the before described characteristics already do (Hudson, Shaaban, & McNamara, 2015).

2.1.2 Maintenance of production lines

All the machines that are part of a production line need maintenance to make sure failures do not happen too often. In the past maintenance was mostly seen as something that “needed to be done” and was primarily used reactively. Reactive maintenance means that no action is taken to prevent failures or to detect failures (Kelly, 1997) (Alsyouf, 2007). Nowadays mostly use is made of proactive maintenance, meaning preventive and predictive maintenance (Swanson, 2001). Firstly, preventive maintenance can be seen as maintenance that is carried out to decrease the probability of failure or the performance degradation of an item, this is done at scheduled time intervals (Alsyouf, 2007) (British Standard, 1984). Another option of proactive maintenance is predictive maintenance. This way of maintenance is focussed on detecting hidden and potential failures and to predict the condition of the equipment (Alsyouf, 2007). Another and more recent approach of maintenance is aggressive maintenance. The aim of this approach is to at the same time improve the equipment performance while also avoiding failures of the equipment (Swanson, 2001) (Sharma, Shudhanshu, & Bhardwaj, 2012). This aggressive maintenance strategy goes beyond only avoiding failures from happening (Swanson, 2001). It also aims at increasing the performance of the system and its equipment during its life-time continuously. The most common form of aggressive maintenance is called “*Total Productive Maintenance*” (TPM). Pomorksi (2004) explained TPM in the following way:

> “*Total Productive Maintenance is a structured equipment-centric continuous improvement process that strives to optimise production effectiveness by identifying and eliminating equipment and production efficiency losses throughout the production system life cycle through active team based participation of employees across all levels of the operational hierarchy*.” (Pomorski, 2004).

The main goal of TPM is to reduce the six “major losses” which are the biggest reasons for a loss of productivity on a production line. This concerns both the quality of the product and the availability of the equipment. These six major losses are the following (Almeanazel, 2010) (Nakajima, 1988) (Rajput & Jayaswal, 2012) (Chan, Lau, Ip, Chan, & Kong, 2005) (Aman, Ezzine, Fattah, Lachhab, & Moussami, 2017):

- *Equipment breakdown or failure losses*: these are time or volume losses that are caused by sporadic or chronic failures of the equipment.
- *Setup and adjustment losses*: these are losses caused by the change of one production item to another production item with different requirements.
- *Idling and minor stop losses*: losses that are caused by a temporary malfunction that causes the production to be interrupted or losses due to the idling of the machine.

- *Reduced speed losses*: this is a loss that is caused due to a slower speed of the machines. This can be a difference between the design speed and actual speed or the design speed and the desired speed.
- *Reduced yield losses*: these are losses caused by the start-up of a machine.
- *Quality defects and reworks*: volume losses due to defect products and rework and time losses due to repair of the defective products to good quality products.

These losses and their effects on the availability of the system are elaborated in the next paragraph.

2.2 Machine Downtime and Reliability

The reliability and the downtime of a system is important with regard to the throughput of the total system. The reliability of a system is defined by the duration of failures and the failure rate. The failure rate is the statistical fluctuation that can be seen in the production output of each machine. The failure rate is the frequency at which failures occur over a certain time period and can be defined as $\lambda(t)$, which measures the number of failures per unit of time (Lehto, Landry, & Buck, 2007). Another way in which this can be expressed and that is often used is the *mean time between failures* (MTBF), meaning the average operating time that exists between two occurrences of a failure and is equal to $1/\lambda$ (Lehto, Landry, & Buck, 2007) (Suehiro, 1987).

The mean time it takes to repair a failure or breakdown at a machine is defined as the *mean time to repair* (MTTR) (Birolini, 2017). The time a machine is down can be categorised in the actual repair time, the administrative delay and the waiting time. Meaning the actual time it takes to repair a failure and the time it takes to wait for or contact the right people and material to be present to repair the machine which is experiencing a failure. When these times are excluded in the availability calculation, it is called inherent availability. If these times are included in the availability calculation it is called the operational availability (Katukoori, 1995). In this thesis the waiting times and administrative delay is included in the MTTR. This has been chosen since this thesis focusses on short stoppages only. The waiting time is usually a large part of the mean time to repair in these short stoppages compared to time it takes for the actual action to be performed which repairs the machines.

Both these factors influence the availability, in this case operational availability, of a machine or system, which can be calculated in the following way (Torell & Avelar, 2004):

$$Availability = \frac{MTBF}{(MTBF + MTTR)}$$

The MTBF can be calculated in two ways. First of all, it can be calculated by the average of all the time periods in between two adjacent stoppages over a certain period of time. Besides that it can be calculated by dividing the number of stoppages in a certain time period by the time that was available for operation in that time period. Which results in the following formula:

$$MTBF = \frac{number\ of\ stopages}{total\ available\ operating\ time}$$

As was explained above, downtime is categorised by two different variables: the mean time to repair and the mean time between failures, respectively about the duration and the frequency of failures (Patti & Watson, 2010). Downtime in itself can also be categorised in planned downtime and unplanned downtime. Planned downtime is the time the system is unavailable whenever this has been planned, for example due to maintenance tasks or because the system is not producing on certain days. Unplanned downtime is all the time the system is down whenever this was not planned to happen and is caused by failures or defects in the system. Downtime can be further categorised in the categories that are displayed in Figure 2.1, which are similar to the "six major losses" defined by the Total Productive Maintenance strategy in paragraph 2.1.2. Each part of this figure is elaborated below.

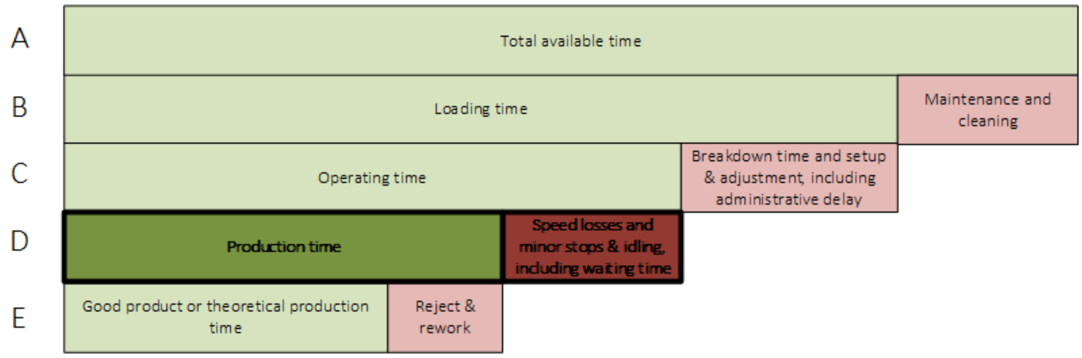

Figure 2.1: Machine downtime categorisation

Figure 2.1 is divided in different levels. Level A and B regard the losses which are known beforehand and occur when the production line is not planned to be producing. These are losses that regard maintenance and cleaning. Level C focusses on losses which are caused by large breakdowns and planned stoppages during production. Level D focusses on losses caused by minor stoppages and idling, the problem on which this thesis is focussed. Level E focuses on quality loss. Each level is elaborated below to give an overview of all the losses which can occur at a production line.

Level A and B: Maintenance and Cleaning: For level A and B the losses can be categorised under planned downtime, as was described before. This level includes loss caused by maintenance of the machines and cleaning of the production line. These tasks all occur during the time that the production line is not planned to be producing. The amount of loss caused due to this can be planned by the management and maintenance departments.

Level C: Breakdown and Setup & Adjustment Losses: The loading time which is displayed in Figure 2.1, is the time the production line is available to be used for production. First of all the availability of the system is influenced by losses caused due to breakdowns, the unplanned downtime. These are usually failures of the equipment that last for a longer time period and are of a technical nature. This means that an analysis needs to be performed to investigate the root cause of the failure on the machine to eliminate this kind of failure in the future (Kiran, Mathew, & Kuriakose, 2013). These losses are also characterised by an amount of administrative delay, meaning the time it takes before the administrative procedures are followed to be able to solve the breakdown (Gay, 2016). Secondly, the availability of the system is influenced by the set-up and adjustment losses, which are part of the planned downtime and are caused by changeovers. A changeover occurs when a production line switches from producing one kind of product to producing another kind of product. This kind of downtime is planned, since it is known beforehand that the production line needs to be changed to be able to produce a different product (Almeanazel, 2010). Both these kind of losses influence the availability of the system. This level is outside the scope of this thesis since the focus is on minor stoppages and not on the larger breakdowns and changeovers.

Level D: Minor Stops & Idling and Speed Losses: When the loss from level C is subtracted from the loading time it results in the left operating time. This is the time that the system is actually in operation. In level D the second category of losses is defined which influences the performance of the system. First of all, the performance of the system is decreased due to losses caused by minor stoppages and idling. A minor stoppage can be defined as a stoppage that arises from an equipment error in an automated process. This means that under normal conditions the equipment would operate automatically without human intervention, but when a minor stoppage occurs it is necessary for the operator to take action to restore the equipment to normal operating condition, which is usually done by resetting and/or reactivating the equipment (Suehiro, 1987). These are usually actions that take the operator no longer than about five minutes (Benjamin, Murugaiah, & Marathamuthu, 2013) (Vorne Industries, 2002-2008). These losses are also influenced by the amount of time that needs to be waited on an operator to become available to solve the stoppage (Benjamin, Murugaiah, & Marathamuthu, 2013). These minor stoppages can influence other machines before or after it on the production line, making these machines go idle. Secondly also speed losses decrease the performance of the system. These are losses that occur when a machine is running below or above its designed speed. This can for example occur due to the fact that because of failures machines are set to a lower or higher capacity. Whenever a machine is operating at a lower speed, this means that less products are produced in the same period of time. When a machine is operating at a higher speed than it is designed for, losses can also occur due to the fact that the machines or the equipment is not made to operate at this speed and for example products are damaged due to that. When these losses are subtracted from the operating time, the time that is left for actual production remains.

Level E: Reject and Rework Losses: Level E defines the final category of losses which are the quality losses. This means that when products do not meet the quality standards, they can be rejected or need rework. This also causes production loss, both in time and the throughput of a production line (Nakajima, 1988). This can either be losses that occur during normal production or losses that occur due to defect products during the start-up of machines. When these losses are subtracted from the available operating time the time that is left is the theoretical production time, meaning the time that the system was actually busy with producing a good quality product. This time eventually determines the output of the production line. For the purpose of this thesis these losses however are outside the scope of what is being investigated.

2.2.1 Minor Stoppages and Idling

From all the above mentioned losses, the losses caused by minor stoppages and idling, which were defined in level D in Figure 2.1, influence the overall equipment efficiency usually the most with a loss of productivity of around twenty to thirty percent of the total available production time (Ljungberg, 1998) (Heineken, 2019). As was stated before the focus of this thesis is on these minor stoppages and idling. For this reason, the failure rate, the rate for these minor stoppages, needs to be taken into account and the larger breakdowns are not considered here. This failure rate, for minor stoppages, can also be renamed as the *Minor Stoppage MTBF* (Suehiro, 1987). Or the name *mean time between assists* (MTBA) can be used, meaning the mean time between two moments when an operator needs to perform an unplanned assist, following from a minor stoppage, to let the machine start again (Heineken Nederland, 2018). The average time a stoppage lasts is of importance as well. In the case of minor stoppages this is the time it takes for an operator to notice the minor stoppage or become available, walk to the equipment and reset or readjust the machine. The time the operator needs for this is usually no longer than five minutes (Benjamin, Murugaiah, & Marathamuthu, 2013) (Vorne Industries, 2002-2008). This time can be defined as the *mean stoppage time* (MST). With the use of these variables the non-availability due to minor stoppages can be calculated with the following equation:

$$Non-availability\ due\ to\ minor\ stoppages = 1 - \frac{MTBA}{(MTBA + MST)}$$

Downtime on a production line is essentially inevitable, as was stated before. The impact downtime has, is however is dependent on several factors. First of all, which kind of downtime it is, as can be categorised by the before explained characteristics. Besides that, also the frequency, the duration and the relationship between these plays a role in the effect downtime has on a production line (Patti & Watson, 2010). In their research Patti & Watson stated that the effect of the frequency of downtimes is dependent on both the protective capacity, which was explained above, and on the time between these failures (Patti & Watson, 2010). All these factors have effect on the blockage and starvation of a production line. These effects are elaborated in the next paragraph.

2.2.2 Buffer Time and Recovery Time Buffers

The impact of a stoppage is dependent on the effect it has on the other machines in the production line and mostly on the effect it has on the bottleneck machine. Whenever a stoppage lasts longer, the chance of either blockage or starvation increases. When the line is not able to cope with a stoppage on one machine this results in other machines becoming either blocked or starved. How fast this happens is dependent on the processing capacities of the machines and the buffers in between them. Usually this is a conveyor belt of which a part has a transportation function and the other part of the conveyor functions as a buffer. The conveyors are responsible to decouple the various individual machines to decrease the impact of a stoppage, by preventing one failure from stopping the whole production process and decrease the total availability of the whole line (Sorgatz & Voigt, 2013). In this way the conveyor belts are responsible for keeping the rest of the production line available and preventing unwanted stoppages of the process (Sorgatz & Voigt, 2013).

To do so, it is important that the buffers have the right fill level. A conveyor upstream of the bottleneck machine should be able to provide materials to the bottleneck, which are called the anti-starve buffers, meaning these buffers are trying to prevent the bottleneck from becoming starved. The conveyors downstream of the bottleneck should be able to absorb the material from the bottleneck and thus prevent this machine from becoming blocked, which are called the anti-block buffers (Sorgatz & Voigt, 2013) (Härte, 1997). This ideal situation is displayed in Figure 2.2, in this case the buffers in front of the bottleneck machine are always full to make sure the bottleneck machine is never starved for material. The buffers after the bottleneck machine are always empty in the ideal situation, this is to make sure that the bottleneck machine is not blocked due to the fact that it cannot place its processed material on the conveyor belt (Hudson, Shaaban, & McNamara, 2015).

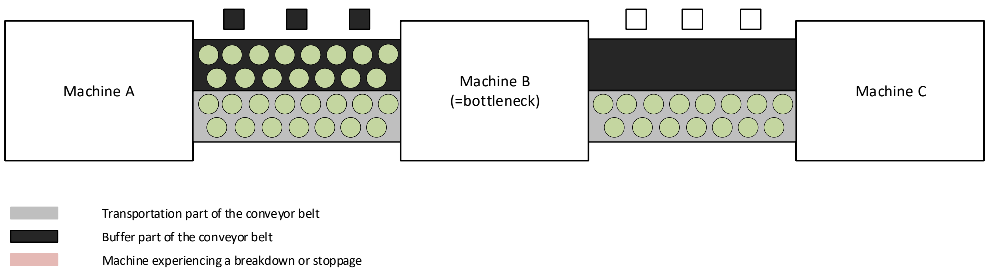

Figure 2.2: Ideal buffer situation

This situation is however not always the case in reality, since failures can occur. The capacity of the buffer in between the machines and the processing speed of the machines determine the extra time in which the failure happening on one machine can be solved before it influences other machines on the production line (Li & Meerkov, 2000). The extra time a machine has before it becomes blocked or starved due to a failure of the machine upstream or downstream, is called the buffer time and can be calculated by dividing the capacity of the buffer by the speed at which the material travels across the conveyor, assuming the buffer is either completely filled or empty before a failure occurs (Härte, 1997). This is however not always the case and for that reason the fill level of the buffer at the moment a stoppage occurs plays a role in the amount of available buffer time (Härte, 1997).

Following from that the buffer time can be calculated using the following formula:

$$buffer\ time = \frac{amount\ of\ products\ on\ buffer}{speed\ at\ which\ the\ products\ travel\ during\ a\ stoppage}$$

This means that whenever a stoppage lasts longer than the buffer time, the stoppage causes starvation or blockage on other machines. For this reason the minimum required mean time to repair that is desirable for a machine can be set equal to the buffer time.

Once a failure has happened and the buffers are not at their nominal fill level they need to be re-established to the ideal state, as is displayed in Figure 2.2, as quickly as possible after the failure. To do so, it is necessary for the machines upstream and downstream to be able to run at a higher capacity compared to the bottleneck machine (Sorgatz & Voigt, 2013). To control this usually sensors are located along the conveyor belts that check at which fill level the buffer is. These sensors are able to give a signal to the machine upstream or downstream of the conveyor belt to let that machine switch to a lower or faster speed or to stop the machine completely.

In Figure 2.3 it is shown what happens whenever a machine upstream of the bottleneck machine experiences a failure. In this case the anti-starve buffer should try to prevent the bottleneck machine from stopping. Looking at this figure it can first be seen that the buffer between machine A and the bottleneck is becoming emptier due to a failure that has happened somewhere upstream of the bottleneck machine. This causes gaps to appear within this buffer, which should be tried to be closed as quickly as possible, but without letting the bottles on the conveyor belt fall. The sensors next to the conveyor belt notice that the conveyor belt is becoming emptier and trigger machine A to start working at a higher speed to restore the buffer to its nominal level (Sorgatz & Voigt, 2013). Machine A, the machine directly in front of the bottleneck can experience a failure as well, this eventually leads to the bottleneck machine becoming starved. The sensors located at the conveyor belt notice that and make sure that the bottleneck machine stops working automatically, before it becomes completely starved.

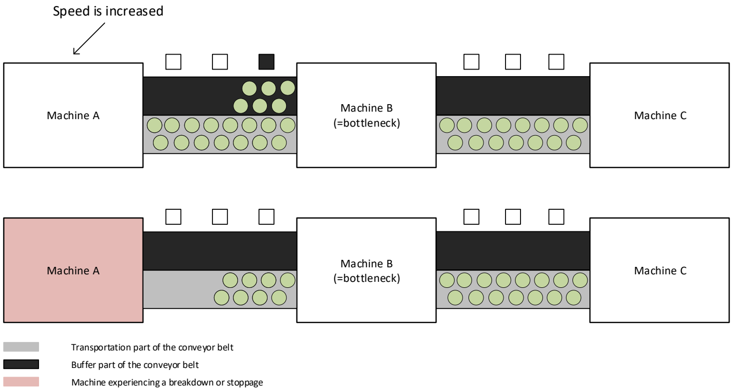

Figure 2.3: Situation when failure occurs on a machine upstream of the bottleneck

In Figure 2.4 it is shown what happens whenever a machine downstream of the bottleneck experiences a failure. When a failure occurs at a machine downstream of the bottleneck the conveyor after the bottleneck starts filling up with bottles (Sorgatz & Voigt, 2013). During this failure machine C first starts to produce at a slower speed, this is done to prevent the bottleneck machine from stopping. When the speed is reduced this means that the conveyor after machine C fills up with a decreased speed and the chance is higher that it is still able to absorb the produced product in the time the failure lasts. Once the failure at the machine downstream is fixed, machine C starts to work at a higher speed to empty the buffer in between the bottleneck machine and machine C itself (Sorgatz & Voigt, 2013). When the buffer is at its nominal fill level again, machine C is working at its nominal speed again. Machine C itself can experience a failure as well, in this case the sensors on the conveyor belt notice that the buffer is becoming fuller, when a certain level is reached it forces the bottleneck machine to stop automatically. Once machine C is working again, the bottleneck machine starts to work after a certain period of time.

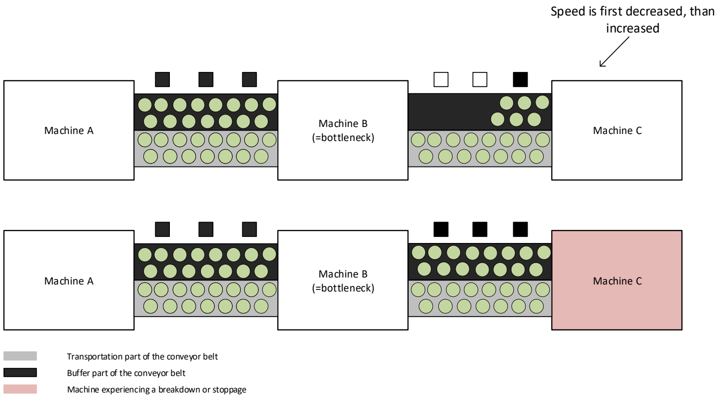

Figure 2.4: Situation when failure occurs on a machine downstream of the bottleneck

The time it takes for the buffer to be recovered to the nominal fill level is called the recovery time, or the depletion and replenishment times (Härte, 1997) (Li & Meerkov, 2000). This time can be calculated by dividing the amount of products that need to be depleted or replenished on the buffer by the difference between the speed of the two machines in between which the buffer is located (Härte, 1997). If it is assumed that the buffer is completely filled or emptied after a failure the recovery time can be calculated with the following formula:

$$recovery\ time\ buffer = \frac{buffer\ capacity}{difference\ in\ speed\ of\ machines\ after\ failure}$$

This means that whenever the mean time between failures is lower than the recovery time the buffer is not at the nominal fill level whenever the next failure occurs. For this reason it can be stated that the minimum required time between failures should be larger than the recovery time. Since in that case the buffers are able to deal better with the next failure.

To conclude, the buffers are responsible for preventing stoppages on one machine from causing other machines to stop as well. This is both dependent on the properties of the conveyor, meaning the amount of products that fit on the conveyor belt and the sensors that are present at the conveyor, the processing capacities of the machines and on the properties of the stoppage itself (Sorgatz & Voigt, 2013) (Patti & Watson, 2010). Meaning the amount of time a stoppage lasts and the amount of time that is between two adjacent stoppages. These factors together form the recovery time of the conveyor belt, meaning the time a conveyor belt needs to restore to its nominal level from the ideal situation as was displayed in Figure 2.2. The buffer capacity of the conveyor determines the effect a stoppage has, since when a stoppage lasts longer than the amount of time that the buffer can handle, the buffer time, it influences the machines upstream or downstream (Patti & Watson, 2010).

In a practical situation however, the ideal situation is not always the case before a failure occurs, meaning that the buffers are not completely full or empty. In this case a stoppage has more effect than originally was thought in means of starvation or blockage of other machines. This aspect is however not researched extensively and the effect it has on the system performance is unclear (Patti & Watson, 2010).

2.2.3 Theoretical Time Concepts

In the previous paragraphs a lot of concepts that define the production time were discussed. In the figure below the relationship and the influence these times have on each other is displayed. The red circles display the negative effect certain time concepts have on the total available time, which is displayed in light green. When the negative effects are subtracted from the total available time this results in total time that is left for operation or production, the other concepts displayed in light green. The concept displayed in dark green is a time concept that positively influences the total available time for production.

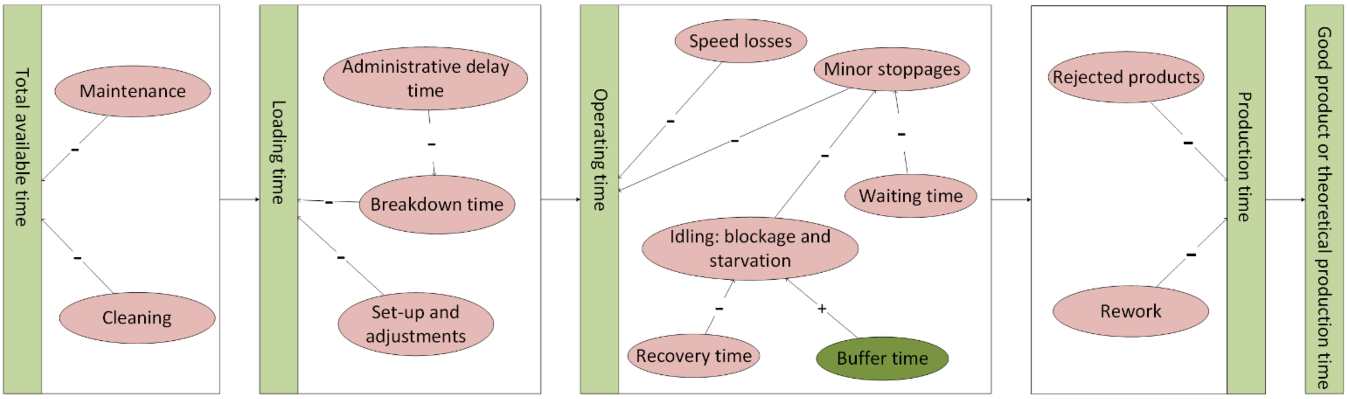

Figure 2.5: Time Concepts Theoretical Framework

2.2.4 Machine Productivity vs System Productivity

Whereas the previously definitions with regard to downtime and availability are mostly focussed on machine level, also the productivity on system level is of importance. These two productivities are dependent upon each other since the performance of a system is dependent on its components (Barabady & Kumar, 2007). To define the system performance based on the performance of the different components a lot of analytical models exist. However, a lot of these models assume that there are no buffers present in between these machines, which does not compare to most situation in the field of practice of production lines (Barabady & Kumar, 2007) (Tsarouhas P. H., 2015). How these buffers can improve the availability of a system was explained in the above paragraph. The level of influence a machine has on the system productivity is first of all dependent on the buffer size that is allocated to that machine. Besides that, it is also important if the machine works in parallel or in series to determine its impact on the total system availability. Next to that, the place the machine has in the total system is of importance since this determines the impact a failure has on the bottleneck machine of the production line. The closer a machine is placed to the bottleneck machine, the more impact a failure of these machines has on the bottleneck.

Due to the fact that all these factors play a role in the situation with regard to system availability, to express these in analytical models is very complex and in a lot of occasions different assumptions that are not comparable to reality have been made. For this reason a lot of researchers that investigate this problem make use of simulation studies (Padhi, Wagner, Niranjan, & Aggarwal, 2013) (Bartkowiak & Pawlewski, 2016) (McNamara, Shaaban, & Hudson, 2012).

2.3 Fish Bone Diagram

In Figure 2.6 all the causes that play a role in the before described problem with regard to inefficiencies of a production line are displayed, the circle on the right displays the problem and the arrows display causes of the problem per category: manpower, machines, material and methods. This figure displays the root causes of productivity loss which can be seen at production lines.

These causes are derived both from the above elaborated literature and from conversations with people from the field of practice. In these conversations certain problems with regard to productivity losses were addressed, which are translated to this figure. In these conversations different causes from the literature were discussed and it was determined if these causes also play a role in the field of practice. This was done by asking multiple operators and managers from production lines what their opinion is with regard to this. If multiple people agreed to certain causes creating a loss of productivity, this loss is incorporated into the figure. The causes that this thesis will focus on are displayed in bold. Furthermore, the effect of these causes on the reliability of the system was also discussed. It was discussed whether these causes have an effect on the frequency of stoppages or/and on the duration of stoppages. Each of the causes that are displayed in Figure 2.6 are discussed below together with their effect on the productivity of a production line.

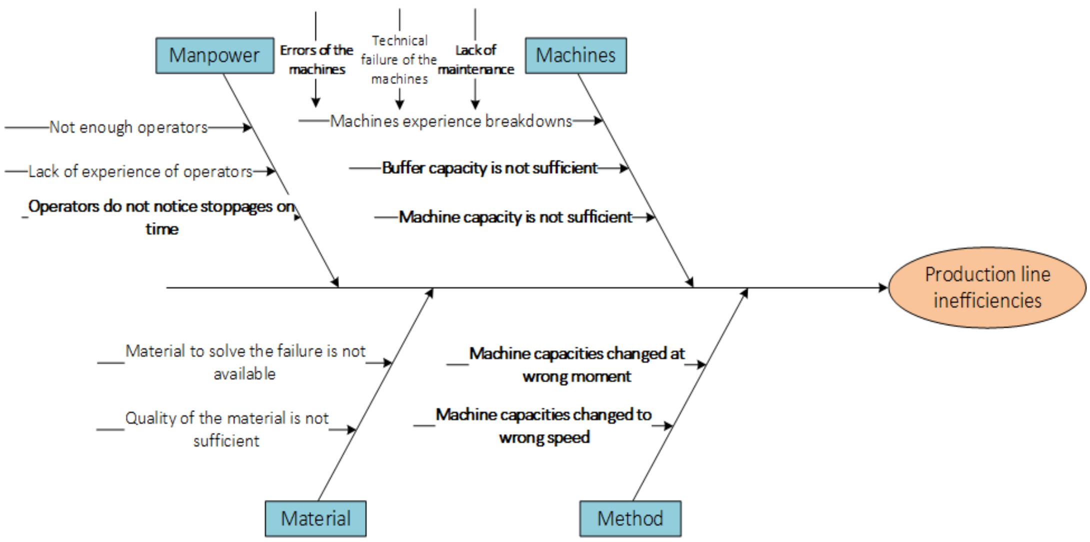

Figure 2.6: Fish Bone Diagram

Manpower

The causes related to manpower have to do with the operators that are present at a production line. First of all, it might sometimes happen that not enough operators are present at the line, meaning that there is more work than the operators are able to handle. Besides, also a lack of experience can contribute to the problem, since for that reason operators might not know how to handle in certain situations. This will result in stoppages lasting longer. Furthermore, it might happen that operators do not notice a stoppage at the moment it happens, which results in a stoppage lasting longer than it would have if the stoppage was immediately noticed. This cause is considered in this thesis in the sense that the mean time to repair of a stoppage will last longer. All the other factors influence the mean time to repair of the failures as well.

Machines

Secondly, causes related to the machines play a role in the problem. First of all, a machine can experience breakdowns and stoppages. These breakdowns can have different causes. It might be caused due to an error in the machines, a technical failure of the machines or a lack of maintenance. The amount of breakdowns and stoppages and the effect of these is mostly dependent on the causes that are specified in the other causes mentioned in the diagram. Besides that, the machines or the buffers that are present between the machines might not have enough capacity to be able to deal with breakdowns or to process the material that is handed to the machines. This causes more inefficiencies in the production process and decreases the mean time between failures. This thesis will focus on productivity loss caused by short stoppages, which can be caused by a lack of maintenance or errors of the machines. The buffer capacity and the machine capacities will be considered in this thesis as well.

Material

Another category which causes inefficiencies of the production process is the available material. Whenever a failure occurs material might be necessary to solve this failure. If this material is not available, this means extra waiting time and a loss of production time, which increases the mean time to repair of a failure. Next to that, the quality of the material might also cause inefficiencies at a production line. Whenever the quality of the needed material is not sufficient enough this might cause machines to breakdown or to slow down, which decreases the mean time between failures. The quality and availability of material is however outside of the scope of this thesis.

Method

The final category of causes is that of the methods which are used. First of all, the machine capacities might be changed at the wrong moment. This is done to prevent machines from going idle, but when this is done too early or too late it might cause the machines to become idle earlier than is possible with other setting. Next to that, the capacities might also be changed to the wrong speed. It might be the case when the capacities of the machines are changed to another speed the production line might be more efficient in coping with stoppages. These methods are both considered in this thesis.

2.4 Balanced or un-balanced lines

To improve the before mentioned problems with regard to inefficiencies of a production line, manufacturing companies can either aim for a balanced or unbalanced production line. Un-balanced meaning that the machines have different mean processing times and balanced meaning that the aim is to have all machines operate at the same mean processing time, which is based on the processing time of the machine with the lowest capacity. The goal behind this is that the production line is producing continuously at the same speed. In this case it is not necessary to add buffers in between the machines, since once material has been processed by one machine it can directly go to the next machine in the system. However, the reality with regard to this is often more complex. This is caused by the fact that the machines of a production line experience failures, as was mentioned in the previous paragraphs. Due to failure on one machine all the other machines are influenced directly, because of a coupling effect. For this reason some authors note that it is better to aim for an unbalanced production line instead of a balanced production line. The reasons these authors state for unbalancing a production line are elaborated below.

In their research *The performance of unpaced production lines with unbalanced mean operation times and unreliability patterns* Hudson et al. (2015) note that the unbalancing of production lines, due to their unreliability, is a somewhat overlooked area of study nowadays, especially in comparison with the mainstream research which focusses on the balancing of production lines (Hudson, Shaaban, & McNamara, 2015). They note that a lot of production lines in the world consist of human operators and machines or tools that can break down and for that reason it is important to investigate the imbalance of production lines (Hudson, Shaaban, & McNamara, 2015). Goldratt (1994) as well noted that a balanced plant is impossible to attain and besides that also undesirable (Atwater & Chakravorty, 1994). This is stated because of the interdependence of the machines on a production line, which means that an interruption at one machine influences the cycle time of the whole system and for this reason it is stated that unbalancing the production line and thus using an extra amount of protective capacity at the non-constraint machines, solves this (Atwater & Chakravorty, 1994). One of the first researches in the field of an un-balanced production line was conducted by Davis (1966) and Hillier and Boiling (1966). They both state that unbalancing a production line is more effective than the balanced variant, but differ in the opinion about in what way to best un-balance a production line (Patti, Watson, & Blackstone Jr, 2008). Hillier and Boiling have founded the so-called "*bowl phenomenon*", which is explained in more detail later on, which says that the machines with the lowest processing time should be in the middle of the production line and the machines with a higher processing time towards the end, together forming a bowl shape. In contradiction to that, Davis (1966) has found that systems with the highest processing time should be placed towards the end of the production line. In the next paragraphs it is discussed with theories exist with regard to the configuration of a production line.

2.4.1 Theory of Constraints and the Drum Buffer Rope Methodology

The machine of the system which has the lowest output and is thus determinant for the total throughput of the system, is called the bottleneck machine. The Theory of Constraints (TOC) is based on this and sees this machine as the constraint of the system. This theory has been developed by Goldratt (1984) and states that every system must at least contain one constraint, which can be defined as any element that limits the system to achieve a higher performance versus its goal (Rahman S. , 1998) (Goldratt E. , 1988). According to the theory the existence of this constraint creates an opportunity for improvement, since these constraints determine the performance of the whole system. If the performance of this constraint is improved, so will the performance of the whole system (Rahman S. , 1998). According to this philosophy continuous improvement can be reached if the following five steps are followed:

1. *Identify the system's constraint(s);*
2. *Decide how to exploit the system's constraint(s);*
3. *Subordinate everything else to the above decision*: this means that the non-constraints of the system must be adjusted to be able to support the constraint of the system, this can be done with the use of protective capacity;
4. *Elevate the system's constraint(s)*: if the existing constraint still performs the worst, it needs rigorous improvements until the system will encounter a new constraint.
5. *If in any of the previous steps a constraint is broken, go back to step 1. Do not let inertia become the next constraint.*

Following these steps leads to the identification of the constraint(s) of the system. This is the one part of the system that is limiting the other parts of the system to perform according to their capacity. The ultimate goal is to eliminate this constraint or facilitate this constraint in such a way that the overall performance of the system is improved.

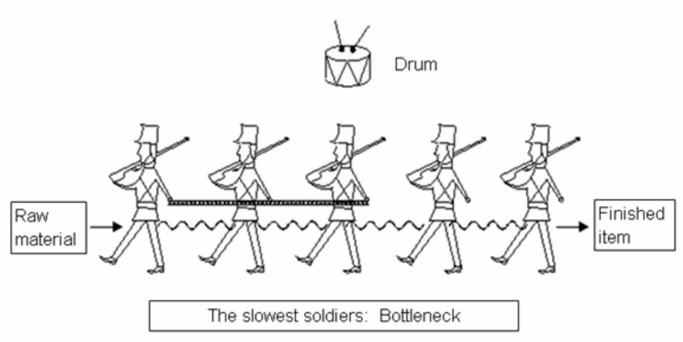

Figure 2.7: Drum Buffer Rope Methodology (Source: Goldratt, 1997)

Derived from the Theory of Constraint is the Drum Buffer Rope (DBR) methodology, which states how the constraint should be facilitated in a production line. This methodology is shown in Figure 2.7. The name of the theory is based on an analogical example (Imaoka, 2012). This example is about a group of soldiers who are marching accompanied by drums. The slowest soldier determines the speed of the march and the rhythm of the *drum* is based on him. In a production line the *drum* is the pace at which the constraint machine(s) work and thus on which the other machines have to be adjusted. To not let the soldier spread from each other they all hold a *rope* to keep them together. In a production line the *rope* is the element that communicates between the critical control points to make sure the system is synchronised. The *buffer* is the strategically placed inventory that protects the output of the system from statistical fluctuations (Rahman S. , 1998) and can be compared to the space of the rope between the soldiers that allows for fluctuations in the speed of the soldiers. According to this theory a production line should be organised in the same way. Meaning that the system needs to be adjusted to the slowest machines of the system and the largest buffer needs to be placed in front of the slowest machine to control the variance of the system. This is done to assure that the system can produce according to the capabilities of the constraint machine (Patti & Watson, 2010).

2.4.2 Kanban System

Besides the before mentioned DBR methodology, the Kanban system suggests another way in order to facilitate a production line to enhance its performance. In this approach it is stated that a production line should be organised in such a way that it perfectly meets the demand. A minimum of the work in-process inventory (WIP) present in the system that is necessary for continuous production should be reached, which means a Just In Time delivery (JIT) (Patti, Watson, & Blackstone Jr, 2008). In the Kanban system a workstation is only allowed to release a processed part whenever the next workstation is ready for that part and thus the waiting inventory is minimized. This means that a finite amount of buffer capacity should be available in between the machines and whenever a maximum of these buffers is reached the upstream machine is told to stop producing (Rahman, Sharif, & Esa, 2013). In the most Kanban systems the buffer capacity is evenly distributed between the buffers that connect the machines. However, the literature with regard to this theory often assumes balanced production lines without a bottleneck machine, this is however often not the case in the more complex situation in the field of practice (Takahashni, Morikawa, & Chen, 2007). In their research Takahashni et al. (2017) looked at the effects of implementing the Kanban system in an unbalanced production line. Here they found that under some conditions the Kanban system outperforms the before described DBR methodology, which was again dependent on the characteristics of the system (Takahashni, Morikawa, & Chen, 2007).

The difference between the two described methodologies and the allocation of buffers is displayed in Figure 2.8 below.

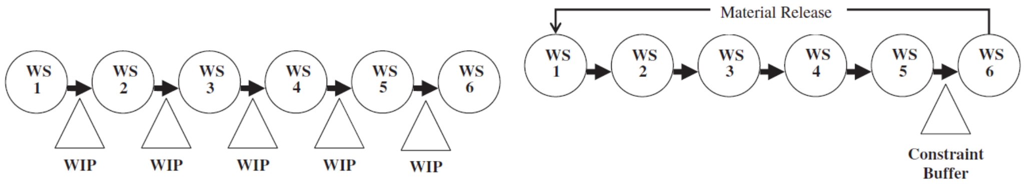

Figure 2.8: Kanban System vs a Drum Buffer Rope System (Source: Patti & Watson, 2010)

2.4.3 Bowl Phenomenon

Next to the before explained methodologies, another approach exists with regard to how the capacities of the machines in the system should be allocated. This theory is called the bowl phenomenon. Another name that companies often use for this configuration of a production line is called the *"V-graph"* or *"V-shape"* (Heineken, 2018). These approaches state that lowest processing times should be located in the middle of a production line and higher processing times at the end and the beginning of the production line (Urban & Chiang, 2016). Due to this a graph representing the processing times looks like a bowl or a "V", hence the name of these approaches.

The effects of the bowl phenomenon have excessively been discussed in the literature. The conclusion in most of these researches is that the effects of the bowl phenomenon on improving the throughput of a production line is dependent on the properties of the production line itself. Pike and Martin (1994) note in their research that a line that is organised following the bowl phenomenon, is more efficient than a balanced production line since the coupling effects, meaning blockage and starvation due to failure on another machine, are reduced by the buffers that are located in between the machines (Pike & Martin, 1994). They however note that this is not always the case since the real situation in a production line is often more complex than the theory states and that its effectiveness is dependent on the characteristics of the production line being investigated. In the research of McNamara et al. (2016) they found that a production line which is designed according to the bowl shape, usually performs the best in case of a production line with high variability, either in the processing time or in the failure behaviour, and in a production line which has a limited amount of buffer capacity (McNamara, Shaaban, & Hudson, 2016). In the research of McNamara et al. (2016) they also discovered that the bowl phenomenon might deal better with breakdowns than a balanced production line (McNamara, Shabaan, & Hudson, 2014). With regard to how the bowl should be allocated it is researched that it should usually be relatively flat in the middle and very steep towards the end of the production line. The degree of imbalance should decrease with the amount of available buffer capacity in between the machines and increase with the length of the line and the amount of variation in the processing times of the machines (McNamara, Shaaban, & Hudson, 2016).

Besides that, the effectiveness of the bowl phenomenon is also dependent on the failure behaviour of the production line, meaning which machines usually fail the most and what the mean time to repair is for the machines. In their research Choong and Gershwin (1987) found that the bowl phenomenon is most effective in production lines where the failure rates are fixed and the repair times constant, or where the stations are becoming less reliable towards the end of the line (Choong & Gershwin, 1987). But Hudson et al. (2015) noticed that articles with the focus on patterns of breakdown rather than total line unreliability, can only be found in a very few articles, although it can be of significant importance. They state that there has not been an attempt to study the area in any systematic way (Hudson, Shaaban, & McNamara, 2015).

2.4.4 Allocation of Protective Capacity

Besides the before mentioned methodologies also different approaches exist with regard to the way in which the extra amount of protective capacity should be allocated to the non-constraint machines. When a non-constraint machine is assigned protective capacity this means it has an extra amount of processing capacity compared to the bottleneck machine. This extra capacity is used to be able to deal with the unreliability and thus failure of the machines, which protects the constraint machine from either becoming blocked or starved. With regard to how the extra capacity at the non-constraint machines should be allocated, different approaches exist. In the research of So

(1989) it is concluded that there is improvement in the efficiency of a production line with finite buffers, when unbalancing the line appropriately (So, 1989). It is however noted that it is important to do this in the appropriate way, since otherwise the efficiency can decrease (So, 1989). What the appropriate way is depends on the variability of the machines, as was also discussed in the above elaborated theories. McNamara et al. (2016) conclude that in most cases unbalanced lines deal better with breakdowns and thus perform better than unbalanced lines. This is however dependent on the characteristics of the system and the way in which the protective capacity is allocated. As Patti et al. (2008) stated in their research, little research has been conducted with regard to the question of the quantity and the position of the protective capacity in relationship with the variation of the system (Patti, Watson, & Blackstone Jr, 2008). Protective capacity can first of all be allocated in a balanced way, meaning all the machines except the constraint machine have the same amount of extra protective capacity (Patti, Watson, & Blackstone Jr, 2008). This way of allocating protective capacity is sometimes also called levelled, equally distributed or flat (Craighead, Patterson, & Fredendall, 2001) (Kadipasaoglu, Xiang, Hurley, & Khumawala, 2000) (Louis, 2003) (Blackstone J. H., 2004).

Besides that, the amount of protective capacity can also be increasing or decreasing, meaning the amount of protective capacity increases or decreases towards or away from the constraint machine (Patti, Watson, & Blackstone Jr, 2008). These shapes can furthermore differ in how they are allocated upstream or downstream of the bottleneck machine. When an increasing and decreasing amount of protective capacity are combined, different shapes can be created. It can have the form of a bowl, a peak, a sawtooth or a reversed sawtooth (Craighead, Patterson, & Fredendall, 2001). In the bowl shape, or also called the valley (Craighead, Patterson, & Fredendall, 2001) or "*V-Shape",* the amount of protective capacity is decreasing towards the bottleneck machine both upstream and downstream of the bottleneck machine, in this way forming a shape that looks like a bowl or a "V". This shape is based on the before described bowl phenomenon. The peak shape is the opposite of this and in this configuration the amount of protective capacity is increasing towards the bottleneck machine, both upstream and downstream (Craighead, Patterson, & Fredendall, 2001). In this configuration the shape of the amount of protective capacity, excluding the capacity of the bottleneck machine, looks like a mountain or a peak, hence its name. A combination of these two shapes can be seen in the sawtooth and reversed sawtooth shape (Craighead, Patterson, & Fredendall, 2001). In the sawtooth shape the amount of protective capacity is decreasing upstream towards the bottleneck and increasing downstream towards the bottleneck machine. The opposite happens in the reversed sawtooth shape in which the amount of protective capacity is increasing upstream towards the bottleneck and decreasing downstream towards the bottleneck (Craighead, Patterson, & Fredendall, 2001). These shapes look like a part of a sawtooth, hence their names. All the above described shapes of protective capacity are summarised in Figure 2.9.

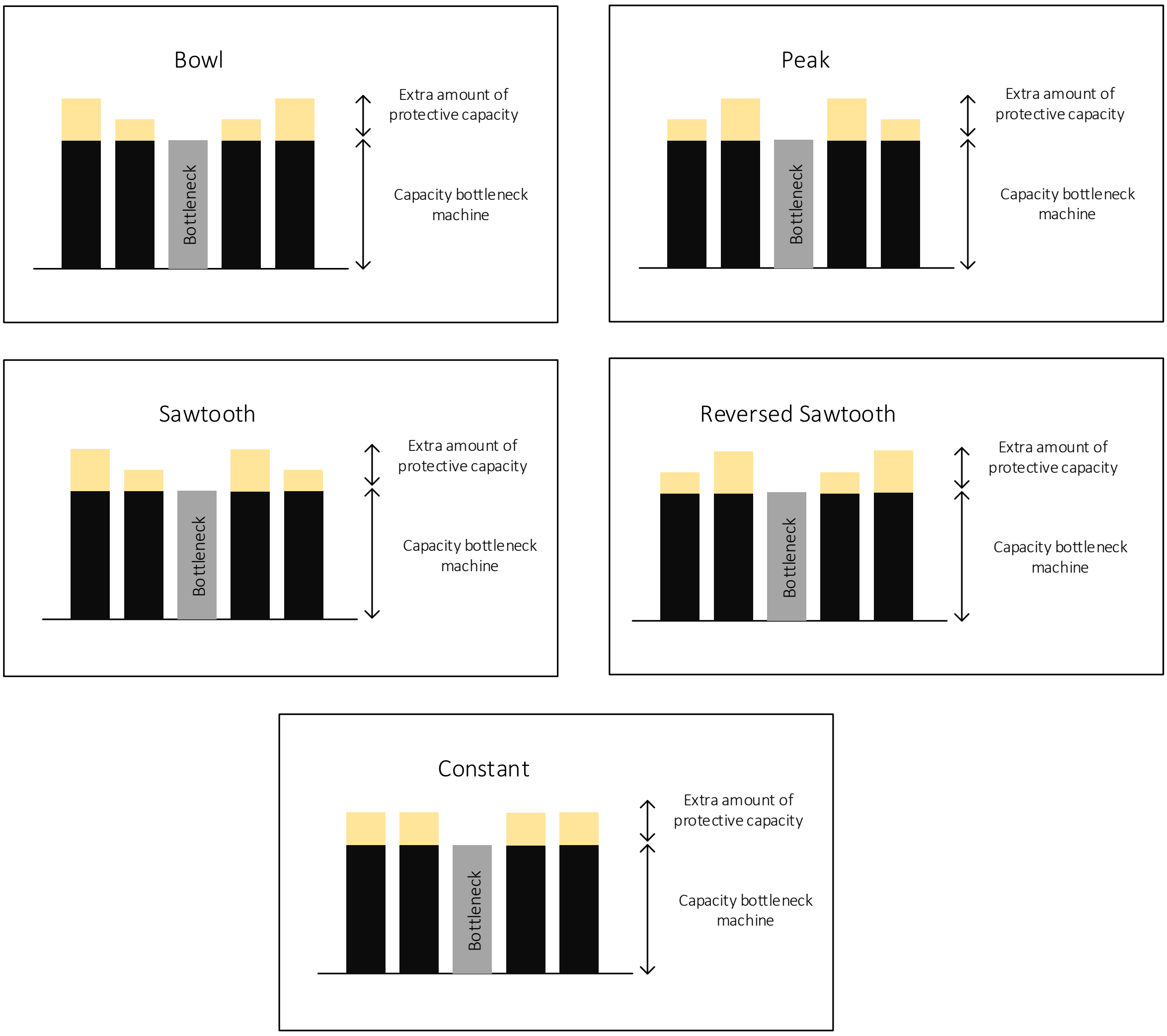

Figure 2.9: Shapes of protective capacity

In their research Patti et al. (2008) looked at both production lines controlled with either DBR or Kanban and found that a balanced use of protective capacity has superior results compared to increasing or decreasing use of protective capacity (Patti, Watson, & Blackstone Jr, 2008). This is the case because a “secondary constraint” appears in the allocation where the protective capacity is either increasing or decreasing, since this machine cannot process all the materials it is given by its predecessor (Patti, Watson, & Blackstone Jr, 2008). From this it can be stated that it is important to not only focus on the “primary constraint” when assigning protective capacity to machines, but also to the fact that due to the protective capacity a “secondary constraint” can appear. However, in this research and the research of Craighead et al. (2001) the only focus was on production lines with machines that had equally distributed downtime. In other research even the only focus was put to the effect of variability in processing time and even assuming all machines reliable. This is not in accordance with most situations in the field of practice, in which some machines are less reliable than other machines.

2.5 Key Performance Indicators (KPI's) production lines

To be able to determine the effects of implementing the before mentioned theories different indicators can be used. The indicator that is used in most literature to measure the performance of a production line is called the Operational Efficiency Effectiveness (OEE). This is calculated by multiplying a measure for quality, a measure for performance and a measure for availability (Almeanazel, 2010). Each of these measures represents a level of losses which was displayed in Figure 2.1.

$$OEE = Availability * Performance * Quality$$

The calculations for these measures that are most commonly used are the following (Pintelon & Muchiri, 2008) (Almeanazel, 2010) (Rajput & Jayaswal, 2012):

Level B and C:

$$Availability = \frac{operating\ time}{loading\ time} * 100\%$$

The availability calculation is based on the losses which were seen in level B and C of Figure 2.1. This measure calculates the availability of the system based on the effect of larger breakdowns. This can be calculated by dividing the operating time by the loading time. The operating time is equal to the loading time minus the total time the system is experiencing unplanned downtime. The loading time is the time that the system is ready to be used for production, this means that the planned downtime is already excluded from the loading time. This results in a percentage that states the availability of the system. These larger breakdowns on which this measure is based are however outside the scope of this thesis.

Level D:

$$Performance = \frac{(theoretical\ cycle\ time\ per\ item * actual\ output)}{operating\ time} * 100\%$$

$$Availability = \frac{operating\ time}{production\ time} * 100\%$$

The performance measure focusses on level D as was defined in Figure 2.1. This measure calculates how well the system is performing with regard to how it would be able to perform without failures. This is done by multiplying the time a cycle would take in theory with the actual output the system has produced and dividing this by the operating time, meaning the time the system should be able to produce minus the time the system is down due to stoppages. This results in the percentage of the performance of the machines or the system. For this thesis this measure is of importance since the total output of the system is influenced by stoppages on the machines and the conveyor belts that are present in between these machines. For this level the availability of the system can be calculated as well. This can be done by dividing the operating time by the production time. The production time is the time that is left for production once the stoppages and speed losses are subtracted from the operating time.

Level E:

$$Quality = \frac{(total\ production - defect\ amount)}{total\ production} * 100\%$$

This measure determines the performance of the system with regard to the quality of the produced products. As was displayed in level E in Figure 2.1. It calculates the percentage of the total production that is defect and thus needs to be rejected in the process. For this thesis this performance measure is outside of the scope of the research and focus should be on the other performance measures.

To conclude, for this thesis the main focus is on the second measure, since the performance is influenced due to stoppages and the effects of these stoppages. This is the measure which focusses on the performance in relationship with the losses that were categorised in level D of Figure 2.1.

2.6 Conclusion

This chapter has discussed multiple concepts and theories with regard to production lines and their productivity. All these concepts and theories are displayed in Table 2.1 below.

Table 2.1: Concepts and theories from Theoretical Framework

Production lines	Properties	Synchronous vs **asynchronous** Paced vs **un-paced** **Infinite** vs finite buffers Reliable vs **unreliable**
	Maintenance	Reactive Preventive Proactive **Aggressive (TPM)**
Reliability	Machine reliability	**Failure rate (MTBF)** **Duration of failures (MTTR)**
	Losses	Breakdown & set-up/adjustment **Minor stops and idling** & speed losses Reject & rework
	Conveyor belts	**Buffer time** **Recovery time**
	System reliability	**Bottleneck**
Increasing Performance	Balanced vs unbalanced lines	**Theory of Constraints** **& Drum Buffer Rope** **Kanban Systems** **Bowl Phenomenon** **Allocation protective capacity**
	Key Performance Indicators	**Performance** Availability Quality

Looking at the different properties of a production line, for this thesis the focus is on an asynchronous, un-paced and unreliable production line with finite buffers. This has been chosen since it is in accordance with the production line being studied in the case study and these properties most realistically present the production lines in the field of practice.

With regard to reliability, both the failure rate and duration of the failures influence the productivity of a system. Furthermore, different kind of losses exist that influence the reliability of the system. However, in this thesis the main focus is on minor stoppages and the idling that is caused by these stoppages as was defined by level C of Figure 2.1. Furthermore, the buffer time and recovery time of the conveyor belts is of importance. They are based on the processing capacities of the machines and capacities of the buffers and determine how well the system is able to cope with failures. Besides that, the total reliability of the system is dependent on the impact the reliability of different machines have on the bottleneck.

When the performance of production lines needs to be improved, different approaches exist with regard to balancing or un-balancing a production line. First of all the Theory of Constraints, which says to focus on the constraint of the system and place the largest buffer in front of this constraint. Secondly, the Kanban system suggest placing equal buffers in between the machines and assuring just-in-time delivery of the products. Thirdly, the bowl phenomenon suggests that the machines with the highest processing times should only be placed at the beginning and end of the production line. However, other research suggest that the highest processing times should be placed at only the end of the production line. All these approaches with regard to unbalancing a production line are based on the allocation of protective capacity to the non-bottleneck machines. According to the literature this can be allocated in a balanced, increasing or decreasing way. Following from this a few different shapes of protective capacity can be considered which were displayed in Figure 2.9 below. These are the constant shape, the bowl shape the peak shape, the sawtooth shape and the reversed sawtooth shape. How much and in which shapes this should be allocated is however not studied extensively.

To measure the productivity of a system three different measures exist: one that measures performance, one that measures availability and one that measures quality. These measures are based on different losses which were defined in Figure 2.1. Since this research focusses mostly on shorter stoppages, the main KPI in this research is the one with regard to the performance of the system. As was defined by the KPI for level C of downtime losses.

3 Generic Model
One-way Bottling and Packaging Process

This chapter elaborates on a generic model of a basic one-way beer bottling and packaging process. This is related to the generic level which was displayed in Figure 1.3. This generic model is used to apply and compare the approaches that were explained in chapter two. In the first paragraph the basic bottling and packaging process itself is elaborated. In the second paragraph a conceptual model based on this generic process is given. The third paragraph gives the improvement alternatives based on the theoretical framework of chapter two that are applied on this generic model. In the fourth paragraph the simulation model that is created to apply and compare these alternatives is explained. The fifth paragraph discusses the results of the experiments based on these alternatives. The sixth paragraph gives the conclusion and the advice and recommendations that can be drawn from this chapter are elaborated in the last paragraph.

3.1 System Description: A One-way Bottling and Packaging Process

In 2010 44.2% of the packaging material that was used for beer by European breweries were glass bottles, of which 19.7% of the total were non-returnable. Besides that, 24.7% of the packaging material was metal cans, which follows a relatively similar process as the one-way, non-returnable glass bottle (Donoghue, Jackson, Koop, & Heuven, 2012). Looking at the Heineken brewery in Zoeterwoude more than half of their production lines are used to package beer in non-returnable glass bottles. Furthermore, 80% of their packaging lines are used for one-way non-returnable packaging, which follows a similar process as the one-way glass bottle (Heineken, 2019).

For the processing of a one-way glass beer bottle this first of all means that the bottles that are used in the process are new and clean when they are entered into the process. This means that no additional machines to clean the bottle are necessary in the process. Looking at the literature a few processes can generally be seen in the bottling and packaging process of a one-way beer bottle (Tsarouhas & Arvanitoyannis, 2010) (Kourtis & Arvanitoyannis, 2001) (Basan, Coccola, & Mendez, 2014) (Härte, 1997) (Priest & Stewart, 2006).

Figure 3.1 shows the generic process that needs to be performed to bottle and package one-way beer bottles.

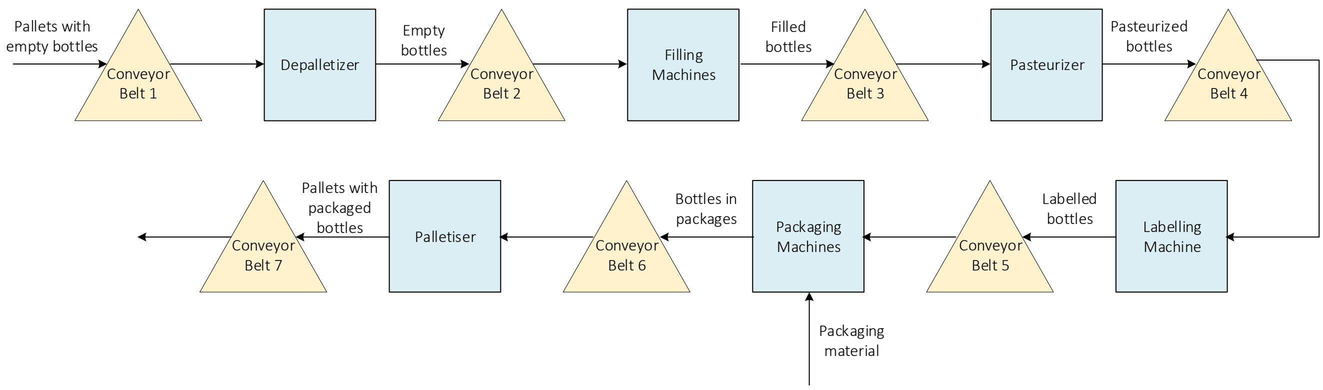

Figure 3.1: Basic bottling and packaging process

The above shown machines, displayed as squares, and conveyor belts, displayed as triangles, that are part of this process can operate both in parallel or in series. The conveyor belts can consist out of multiple sections. Usually the bottleneck machine is either the filling machines or the pasteurizer, since these processes take the longest due to the technical difficulties of the processes (Priest & Stewart, 2006) (Härte, 1997) (Heineken, 2019). The above shown process consists out of multiple machines and multiple conveyor belts. The properties for both of these are elaborated below.

3.1.1 Machines

The machines that are part of the system have different properties. The most important ones are the processing times of the machines and the reliability of the machines.

Processing Time
Each machine has its own processing time. This is the time it takes for the machine to process one or multiple items. Usually this time is defined in the amount of items it can process in an hour or minute. This processing time can be varied over time, meaning that is sometimes processes at a higher or lower processing time than its mean processing time (Blackstone & Cox III, 2002).

Reliability
As was defined in the previous chapter, the machines that are part of a production line are unreliable. This is the case, since every machine is subject to failure. Each machine has its own reliability, which can be defined with a *mean time between failures* and a *mean time to repair* for each machine (Tsarouhas & Arvanitoyannis, 2010). These values can be expressed using multiple kind of distributions. The mean time to repair is dependent on several factors, which include the reaction time of the operators at the production line, the availability of tools to fix the stoppage and the amount of operators that is present at the line.

3.1.2 Conveyor Belts

The conveyor belts also have different properties that are of importance for the generic model. These are the capacity or length of the conveyor and the speed of the conveyor.

Conveyor Length or Capacity
The length of the conveyor determines the amount of bottles that can fit on the conveyor, meaning the conveyor capacity. Part of this capacity is used for transportation purposes and part of this conveyor is used as a buffer (Sorgatz & Voigt, 2013). The amount of buffer capacity that is available on the conveyor belt is also determinant the performance of the system.

Conveyor Speed
The speed of the conveyor determines if the bottles that are put on the conveyor by a machine can be handled by the conveyor (Sorgatz & Voigt, 2013). Usually the conveyor operates at the same or a faster speed compared to the machines to which it is connected, to be able to transport the bottles quickly to the next machine without letting the bottles fall. How fast a bottle arrives at the next machine is thus dependent on both the length and the speed of the conveyor.

3.1.3 Steps in a Bottling and Packaging Process

In Figure 3.1 the generic bottling and packaging process of one-way beer bottles was shown. This process consists out of different steps. Every step is elaborated below.

Step 1: Conveyor 1 → Depalletiser → Conveyor 2
Usually the process starts with pallets that are filled with empty bottles entering on a conveyor belt. These bottles need to be removed from the pallet by a depalletiser. This machine removes the empty bottles layer per layer and finishes with putting the empty bottles on a second conveyor belt to be transported to the next machine (Basan, Coccola, & Mendez, 2014).

Step 2: Conveyor 2 → Filling and Rinsing Machine → Conveyor 3
This second conveyor belt brings the empty bottles to the rinsing and filling machine that cleans the bottles and fills them with beer (Priest & Stewart, 2006). In this process also a crown cap is placed on the bottles. Once this process has been finished the filled bottles are put on the next conveyor belt.

Step 3: Conveyor 3 → Pasteurizer → Conveyor 4
The third conveyor belt transports the filled bottles to the next machine in the system, which is the pasteurizer. This machine heats the bottles to a certain temperature to postpone the expiration date of the beer. This is done for a certain period of time which is usually between 45 minutes and one hour. Once this process is finished, the bottles move on to the next conveyor belt (Härte, 1997).

Step 4: Conveyor 4 → Labelling Machine → Conveyor 5
The fourth conveyor belt transports the pasteurized bottles to the labelling machine. This machine puts the right labels on different parts of the bottles and after that the labelled bottles are moved onto the next conveyor belt (Kourtis & Arvanitoyannis, 2001).

Step 5: Conveyor 5 → Packaging Machine → Conveyor 6
The fifth conveyor belt moves the labelled bottles to the machine that packages them. This is usually done by a couple of different packaging machines, that together package the beer in boxes. This means that not only filled and labelled bottles are needed for this process, but also boxes in which the bottles can be packaged (Priest & Stewart, 2006). Once this packaging process is finished the boxes are moved onto the next conveyor belt.

Step 6: Conveyor 6 → Palletiser → Conveyor 7
The sixth conveyor transports the boxes to the final machine of the process; the palletiser. This machines organises the boxes in such a way that they can be put together on a pallet in multiple layers (Priest & Stewart, 2006). Once this process is finished, the pallets are moved on the final conveyor belt which brings them either to a storage area or directly to be transported. Once the pallets are moved onto the final conveyor belt the process is finished.

3.2 Conceptual Model

From this generic system description a conceptual model is created, which is used to carry out different experiments. To be able to model this system, which was displayed in Figure 3.1, certain properties of to the system can be varied or need to be assumed. These properties are elaborated in the next paragraphs. First the properties which are considered for the machines are elaborated, next the properties of the conveyors are explained and finally the other assumptions that are made to model the system are explained.

3.2.1 Machines

With regard to the machines the properties that can be varied are the processing times of the machines and the reliability of the machines. The configurations that are used for these properties are elaborated below.

Processing Times
For each machine a constant processing time is assumed in operating condition, since in reality there is very small variation in the processing times of the machines under stable conditions. In the system description it was stated that in this generic model the pasteurizer is assumed as the bottleneck machine of the production line. For this machine a maximum processing time of 80,000 bottles per hour is assumed. This value is derived from the actual processing time of this machine on different production lines (Heineken, 2019). For the other machines that are part of the system, the processing time is assumed to have a higher limit, to be able to test the impacts of the improvement alternatives, which are elaborated in the next paragraph. Their processing times are determined based on the amount of protective capacity that should be allocated to them, based on different approaches.

Reliability of the Machines
Besides that, also the reliability of the machines needs to be considered. In the conceptual model the failure behaviour is assumed to consist out of a mean time to repair and a mean time between failures. For the mean time to repair an exponential distribution with a mean time of one minute is assumed. This mean is derived from the mean time of a short stoppage on machines that are part of bottling and filing packaging lines (Sorgatz & Voigt, 2013)(Heineken, 2019) (Verwaal, 2018) (Battini, Persona, & Regattieri, 2009). For the mean time between failures a few different configurations are considered, all three exponentially distributed. The first three configurations are

one machine that is less reliable, either located upstream, in the middle or downstream. The most unreliable machine is assumed to have a reliability with a mean time between failures of 5 minutes and the other machines are assumed to have a mean time between failures of 20 minutes. The fourth configuration considers all machines having the same reliability, with a mean time between failures of 15 minutes for each machine. These mean time between failures are derived from the most unreliable machines of bottling and packaging production lines (Heineken, 2019) (Scholten, 2016).

3.2.2 Conveyor Belts

With regard to the conveyor belts the property that can be varied is the buffer capacity of the conveyor belts. The configurations that are used for this property is elaborated below.

Conveyor capacity
For the conveyor belts the property that is varied is the number of bottles that fits on the conveyor belt. For the conceptual model three kind of configurations are considered; a small buffer capacity, a medium buffer capacity and a large buffer capacity. The small buffer contains 240 bottles, the medium buffer capacity contains 2400 bottles and the large buffer capacity contains 9600 bottles. These values are derived based on buffer capacities seen at various production lines and mentioned in the available literature (Heineken, 2019) (Härte, 1997).

3.2.3 Assumptions

Besides the different configurations that are considered for the machines and conveyor belts, also different assumptions need to made to create the conceptual model. These assumptions are elaborated below.

Conveyor speed
The conveyor is assumed to work at a speed at which it is able to transport all the bottles that the machines put on the belt.

Operators
In this conceptual model the operators are not being considered. Whenever a machine fails, the time it takes for an operator to respond to this failure is included in the *mean time to repair* of the machines.

First and last machine of the production line
Another assumption that is made is that the first machine of the line is never starved of equipment and the last machine of the line has always place to put its processed material. In reality it can happen that the department that is responsible for the brewing of the beer or the supply of the material also has some failures and for that reason they cannot supply the equipment to the production line. The same can happen at the end of the production line meaning that there is no place in the storage to put the materials or the machines used for storing the pallets are broken. Because these are external factors, they are outside the scope of this thesis and the assumption is made that these problems do not occur.

Start-up periods and planned stoppages
For this conceptual model the start-up periods and planned stoppages of a production line are not taken into account since the behaviour of the system is studied whenever this is in a steady state.

Rejection of bottles
For the conceptual model it is assumed that during the process no bottles are rejected due to the fact that these do not meet the quality standards.

Serial machines
All machines are assumed to work in series in the conceptual model. In the field of practice often a combination between serial and parallel working machines can be seen. It is however chosen to model this system as a serial system since in the field of practice if often happens that both machines experience failures at the same time

(Heineken, 2019). A high mean time between failures is assumed which corresponds with the failure behaviour of two parallel working machines.

Bottleneck machine

In this conceptual model of the generic process it has been chosen to model the pasteurizer as the bottleneck machine. This has been chosen since this machine is often seen as the bottleneck machine in situations in the field of practice as was explained in paragraph 3.2.1. This means that the results of this generic model are limited by the fact that this machine is chosen as bottleneck.

3.2.4 Configurations Conceptual Model

Based on the above given assumptions for the conceptual model, some different configurations are proposed which are used as input values for the conceptual model. This conceptual model is based on the system which was explained in Figure 3.1. These configurations are also used as input for the improvement alternatives that are elaborated below. The different configurations are displayed in Table 3.1.

Table 3.1: Different configurations conceptual model

Machines	Maximum processing capacity [bottles/hour]	MTBF [minutes]	MTBF very unreliable [minutes]	MTTR [seconds]
Depalletiser	104,000	20 minutes	-	60 seconds
Filling Machines	104,000	20 minutes	5 minutes	60 seconds
Pasteurizer	80,000	20 minutes	-	60 seconds
Labelling Machines	116,000	20 minutes	5 minutes	60 seconds
Packaging Machines	104,000	20 minutes	5 minutes	60 seconds
Palletiser	116,000	20 minutes	-	60 seconds

3.3 Improvement Alternatives

Based on the theory and the information from the field of practice that was elaborated in the previous chapters some improvement alternatives are proposed to improve the productivity of the production line. The first alternative is based on the way in which the protective capacity is allocated to the machines on the production line. The second alternative is based on changing the amount of buffer capacity that is allocated in between the machines and how the machines are controlled by the sensors which are placed along the conveyor belts. Furthermore, the failure behaviour can have effect on the productivity of a production line. Within these two other alternatives the failure behaviour of the machines is altered to investigate what the influence is of certain failure patterns.

3.3.1 Protective Capacity

As was stated in the theoretical framework different approaches exist with regard to how the protective capacity should be allocated to the machines on a production line in relationship with the bottleneck and how high these capacities should be compared to the bottleneck machine.

Shape of the protective capacity

Allocation of protective capacity can be designed in different shapes that allocate a certain extra amount of protective capacity to the machines upstream and downstream of the bottleneck. The shapes that are considered are the bowl shape, the constant shape, the peak shape, the sawtooth shape and the reversed sawtooth shape, as follows from the theoretical framework and Figure 2.9. In paragraph 2.2.4 these shapes and the reasons behind their names, as are used in the literature, were explained.

The fist allocating of protective capacity for the generic model is the bowl shape and is displayed in Figure 3.2 below.

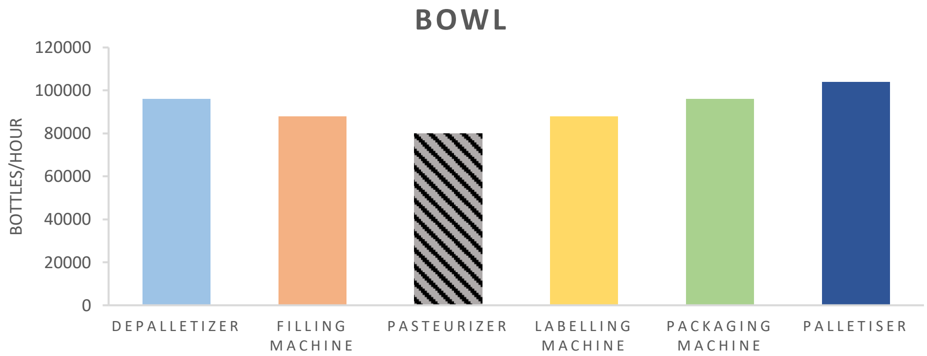

Figure 3.2: Protective capacity bowl shape

From the bowl phenomenon it follows that the protective capacity should be allocated with decreasing amounts towards the bottleneck, in this way the graph of these capacities looks like a bowl.

The opposite allocation of the bowl, can be seen in the peak allocation. When this allocation is used the highest amount of protective capacity is given to the machines next to the bottleneck to prevent these machines from either becoming blocked or starved. This means that the amount of protective capacity is increasing towards the bottleneck machine. This allocation is displayed in Figure 3.3.

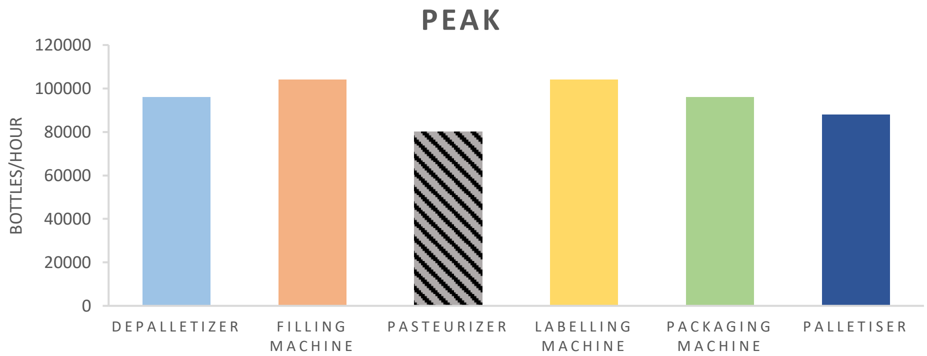

Figure 3.3: Protective capacity peak shape

Besides that, in literature also an allocation in the shape of a sawtooth, or reversed sawtooth is suggested. In the sawtooth shape the amount of protective capacity upstream is decreasing towards the bottleneck machine. Downstream the highest amount of protective capacity is however located closest to the bottleneck machine and decreasing towards the end of the production line. This allocation is displayed in Figure 3.4.

Figure 3.4: Protective capacity sawtooth shape

The reversed sawtooth is the exact opposite of the sawtooth allocation and is displayed in Figure 3.5.

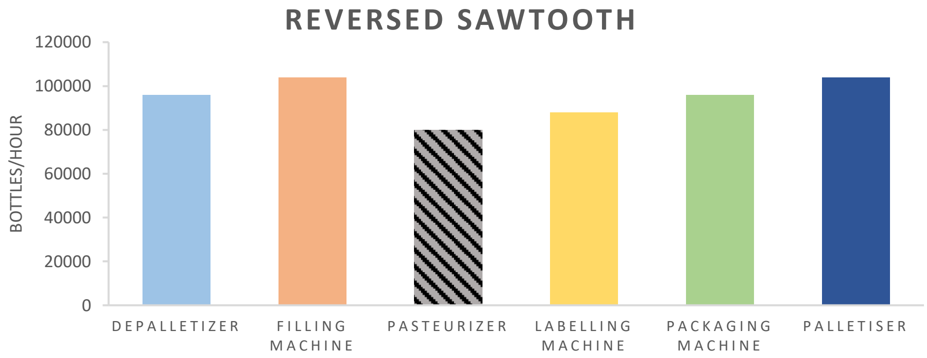

Figure 3.5: Protective capacity reversed sawtooth shape

Finally, another allocation can be made by giving all the other machines besides the bottleneck machine a constant or balanced amount of protective capacity, so no secondary constraint appears, as was suggested in the article of Patti et al. (2008). How the capacities need to be divided when this allocation is followed, can be seen in Figure 3.6.

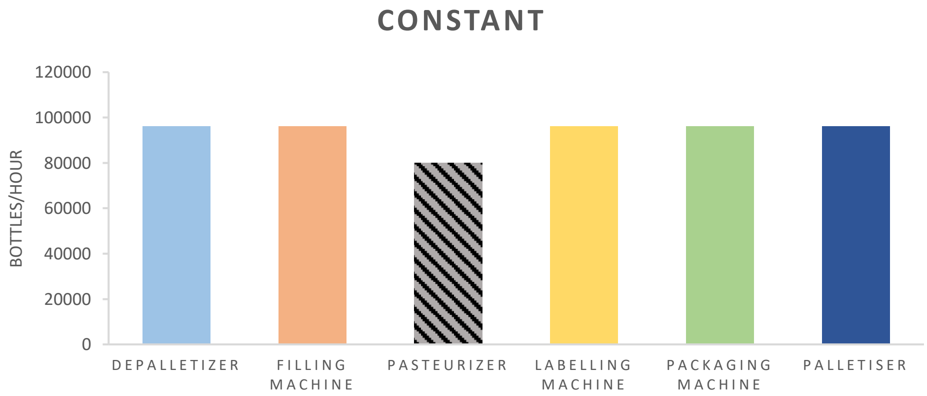

Figure 3.6: Protective capacity constant shape

Amount of protective capacity

Besides the shape of the protective capacity which can be allocated in different ways, also the amount of protective capacity can influence the productivity of a production line. In the conceptual model the protective capacity needs to be divided among five machines. In the previous figures an increase of steps of 10 percent of protective capacity was assumed. For this thesis alternatives of steps of five, ten or fifteen percent are considered for the decreasing and increasing amounts of protective capacity. For the constant amount of protective capacity a difference of ten, twenty and thirty percent is considered.

3.3.2 Conveyor Belts

Besides the way the protective capacity is allocated, also the way in which the conveyor belts are controlled can be altered to increase the productivity of a production line. First of all this is dependent on how much buffer capacity is located in between the machines, more buffer capacity can increase the performance, but only to a certain extent. Different configurations with regard to buffer capacity are applied on the conceptual model.

As was explained in chapter two, the buffers can also be controlled with sensors that activate the protective capacity at a certain fill level of the buffer. At which fill level these sensors need to be placed is not exactly known. Usually they are placed during the installation of the production line by the fabricant. To investigate at which levels these sensor should be activated to have the highest performance of the system, four different alternatives are applied. Upstream a fill level of 30, 40, 50 and 60 percent and downstream a fill level of 40, 50, 60 and 70 percent is considered. These numbers are chosen since the fill level upstream should always be as high as possible and downstream as low as possible in the ideal situation which was described before and could be seen in Figure 2.2.

3.3.3 Reliability Patterns

As was stated in the assumptions, different reliability patterns are considered with regard to the above mentioned improvement alternatives. These different reliability configurations are the following; a production line in which all the machines have the same reliability, a production line in which a machines downstream of the bottleneck is less reliable, a production line in which a machine upstream of the bottleneck is less reliable and a production line in which a machine in the middle is less reliable. From this a conclusion can be drawn if there exists a difference in which alternative works best in which situation and what the influence of such reliability patterns is on the productivity of a production line.

3.4 Simulation Model of the Conceptual Model

Following from the assumptions in the previous paragraph and the system that is seen in Figure 3.1, a simulation model of the basic bottling and packaging process is made. This simulation model can be seen in Figure 3.7. This simulation model is used to apply the before described alternatives on and compare them with each other.

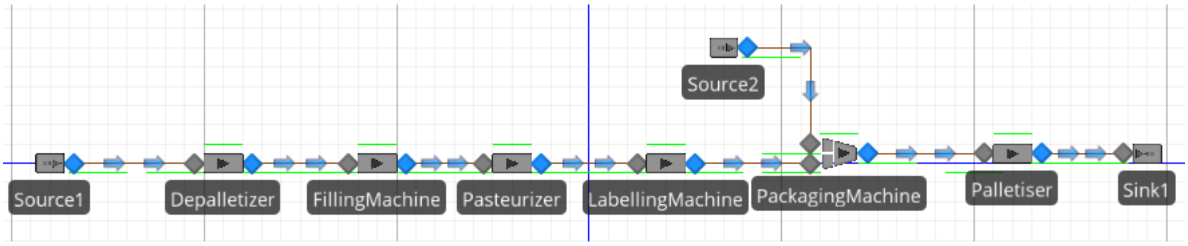

Figure 3.7: Conceptual model simulation

The machines that are part of the production process are modelled in Simio as a *Server*. The properties that can be given to a *Server* correspond with the properties explained in the previous paragraphs. The conveyor belts can also be modelled in Simio as *Conveyors*. To model the packaging machine use is made of a *Combiner,* which combines 24 bottles with one box. The properties which can be given to the *Server, Conveyor* and *Combiner* are explained in Appendix B.

The above explained simulation model is used to apply and compare the alternatives that were elaborated in the previous paragraph 3.3.

3.4.1 Verification of the Conceptual Model

To verify the simulation model it is necessary to check if the behaviour of the model is according to what is expected. This is done by adding labels to the model that check if the input variables are indeed as they are put in the model. These labels check respectively the capacity of the conveyor belt and the processing times of the machines. The failure behaviour should be verified as well. This is also done by adding a label which checks the number of occurrences of a failure for all the machines. Finally, it also needs to be checked if the number of bottles and boxes in the system is correct and thus if entities are being destroyed.

To verify if the model is behaving correctly a buffer capacity of 2400 bottles and 100 boxes is given to all the conveyor belts and a processing time of 80,000 bottles per hour is given to all machines. This means a processing time of 0.045 seconds for processing one bottles and 1.08 seconds for processing one box. An equal reliability is assigned to all the machines with a mean time between failure of 15 minutes.

When running the model with these properties it follows that the model is indeed behaving correctly, since the processing times are all 0.045 seconds and 1.08 seconds, for machines processing bottles and boxes respectively. The occupied buffer capacities are below 2400 bottles or 100 boxes. Furthermore, for the failure behaviour it was seen that each machine is experiencing failures. For the number of bottles or boxes in the system this does not exceed the number of 5*2400+4=1204 bottles and 102 boxes and is thus behaving as is expected.

3.4.2 Validation of Conceptual Model

To validate the simulation model it needs to be checked if the model is behaving according to reality. Since this model is a generic model it cannot be compared to the performance of a real production line and for this reason performance validation is not possible.

Data Validation

The data that has been used as input for the model also needs to be validated. To do so it needs to be checked if the used data in the model is realistic. For the processing times of the machines this can be done by comparing those to machine specifications of the particular machines in other production lines.

*Depalletiser***:** For the depalletiser the highest processing time that is assigned to this machine in the 10% protective capacity configurations is 96,000 bottles per hour. This is the same capacity as one model of depalletiser that is present at a production lines and can thus by said to be valid. In the 15% protective capacity configuration the highest processing speed however is 104,000 bottles per hour. The before mentioned model is able to process maximum 100,000 bottles an hour, but looking at different model depalletisers which are used at other different production lines they have a maximum capacity of 108,000 bottles per hour. This means that also a processing speed of 104,000 is valid.

Filling Machines: In the 10% protective capacity configuration the highest processing time that is assigned to the filling machines is 96,000 bottles per hour and in the 15% protective capacity configuration 104,000 bottles per hour. Some filling machines at different production lines have a maximum capacity of 65,000 bottles per hour, meaning 130,000 bottles per hour when two machines are used, which is often the case in bottling and packaging production lines. From this it can be concluded that the input data for the processing capacities of the filling machines are valid.

Pasteurizer: The pasteurizer is assumed as bottleneck in all the configurations and has a processing capacity of 80,000 bottles per hour. This value is derived from the pasteurizer of different production lines and for that reason can be said to be valid.

Labelling Machines: For the labelling machines in the 10% and 15% protective capacity allocation the maximum processing capacities are 104,000 and 116,000 bottles per hour respectively. Labelling machines at different production lines are able to maximally process 60,000 bottles per hour and also of these often two are used, meaning a maximum capacity of 120,000 bottles per hour. From this it can be concluded that the input values are valid.

Packaging Machines: The maximum processing capacities that are assumed for the packaging machines in the 10% and 15% protective capacity configuration are 96,000 and 104,000 bottles per hour. Packaging machines have found to be able to process 38 boxes per minute, meaning 54,720 bottles per hour for each machine. For two machines this is a processing capacity of 109,440 bottles per hour. From this it can be concluded that the input data for the processing capacity of the packaging machines is valid.

Palletisers: For the processing capacities of the palletisers the maximums are 104,000 and 116,000 bottles per hour respectively for the 10% and 15% protective capacity configuration. Palletisers exist with capacities of around 4000 boxes per hour, meaning 96,000 bottles per hour. Usually use is made of two palletisers for one production line, which means that both input values for the processing capacities are valid.

For the buffer capacities both small, medium and large buffers are considered. All three buffer sizes can be seen at different production lines and in the literature and can be considered valid for that reason.

The reliabilities that are used as input data are based on one of the most unreliable machines of different production lines seen in the field of practice and production lines discussed in the literature, as was explained in paragraph 3.2.1. This means that in reality some machines have higher reliabilities compared to how they are modelled in the generic model. However, some machines in the field of practice perform according to this reliability and for that reason these reliabilities can be considered valid.

Structural Validation

To validate the structure of the model, it is checked how the model performed if variables in the model are minimized or maximized. First of all, it is checked how the model performs when the buffer capacities that are available in between the machines are either maximised or minimised. When the buffer capacities are made very small, the throughput of the model is indeed lower. On the other hand, when the buffer capacities are made very large this resulted in a higher throughput. From this it can be concluded that the model performed valid with regard to the buffer capacities.

Secondly, it is checked what happened when all the machines of the production line are made reliable, this resulted indeed in maximum throughput of the system. When the machines are on the other hand made even more unreliable than was assumed in the generic model, the throughput minimized. From this it can be concluded that the failure behaviour of the model is also valid.

Furthermore, validation can also be carried out by asking experts in the field. From this it could be concluded that the model is indeed behaving like a production line. The output values that are created are however high compared to the situation in the field of practice. This can be explained by the simplicity of the model and only taking short stoppages in account.

3.5 Experiments Generic Model

Based on the improvement alternatives and the conceptual model that were elaborated in the previous paragraphs, experiments are carried out. First of all, an experiment is run based on a base case, to which the other experiments can be compared. After that, experiments with regard to the amount of protective capacity are ran, which are elaborated in the third paragraph. In the next paragraph the results with regard to the experiments on buffer capacity are discussed. In Appendix A the details of the input values that are used for the different experiments can be found.

3.5.1 Experimental set-up

Before the experiments can be ran, some experimental factors need to be determined. These are the run length, the number of replications and the warm-up period of the simulation run. Each of them is elaborated below.

Run Length

For the experiments a run length of **24 hours** is chosen. This has been chosen since usually a production line runs for all 24 hours of a day, which contains three shifts of eight hours. Besides that, in this thesis it is chosen to leave the start-up and change-over times out of scope. For that reason a continuous run length of 24 hours is used. Looking at the failure behaviour of the machines, with a mean time between failure of 20 minutes, this means that a lot of failures can occur in this run length, which is sufficient enough to draw conclusions from. This run length is not too small, so the results should be reliable, but also not too big, which would mean that the time an experiment would take would last longer, which is not practical.

Number of Replications

To make sure the results of the experiments do not rely on coincidence, multiple replications of the experiments need to be carried out. When however a very high amount of replications is chosen it may cause the experiments to last for a very long period of time. For a single scenario experiment of the conceptual model it takes about eight minutes to complete ten replications. In this case the 95% confidence interval is a deviation of the mean of approximately one percent. When choosing to run 20 replications, this takes about fifteen minutes to run a single scenario experiment. The results can be given with a 95% confidence interval with a deviation from the mean of about 0.5%. However, when multiple scenarios need to be considered, this can mean that an experiment can last for over more than an hour. For this reason the number of **10 replications** has been chosen.

Warm-up Period

At the start of a run the bottles first need to get from the first machine to the last machine and are at that moment in a transient state. This transient state changes to a steady state after a certain period of time. This period of time should be equal to the warm-up period of the model, since for this thesis the focus is on the steady-state behaviour. In this model it takes 10 minutes for the first bottle to arrive at the last machine, this means that the warm-up period should be set equal to **10 minutes**.

3.5.2 Base Case

To test the effectiveness of the experiments, they are tested against a base case configuration. In this configuration there is a very small amount of buffer capacity, one very unreliable machine and all machines have an equal processing time. The small amount of buffer capacity that is allocated between the machines is a capacity of 48 bottles. This buffer is only able to absorb very small failures, but most failures influence the whole production line. The most unreliable machine, in this configuration the filling machine, is placed at the beginning of the production line, since this influences the overall throughput of the production line the most. For the reliability of the machines the numbers from Table 3.1 are used. Finally, the machines are set at an equal processing time of 80,000 bottles per hour, since in that way a stoppage has the most effect on the total productivity of the line.

Running an experiment with this configuration resulted in an average throughput of 58,338 bottles per hour, which results in an average performance of 72.9% as can be seen in Table 3.2. The details of the results of these experiments can be found in Appendix B.1.

Table 3.2: Results base case generic model

Base case average throughput [bottles/hour]	55,137
Base case average performance [%]	68.9%
95% Confidence interval	±1.0%

3.5.3 Experiments Protective Capacity

Because there are a lot of configurations that need to be tested for the protective capacity, to limit the amount of experiments it is firstly determined for a constant amount of buffer capacity what the most effective shapes are for different configurations with regard to reliability. For this purpose the medium amount of buffer capacity is used, being 2400 bottles. When this amount is used the buffer is not sufficient to absorb all failures, but is able to absorb some of them. For the amount of protective capacity first all different shapes are compared when they are incrementally increased with 10%. For the most effective shapes, it is compared what happens whenever the steps are incrementally increase with either 5% or 15%. For every experiment the significance is checked using independent two-sample t-tests with a significance level of 0.05.

Shapes of Protective Capacity

This paragraph elaborates on the results of the experiments for different reliability configurations in which the different shapes of protective capacity are compared.

All machine equal reliability: In Figure 3.8 the results with regard to the performance KPI of the system, which was defined in the second chapter, are displayed. This is based on throughput of the experiments in which all the machines have an equal reliability. In this figure the results are displayed as the difference between the outcomes of the experiments and the base case, which was explained in the paragraph 3.5.2.

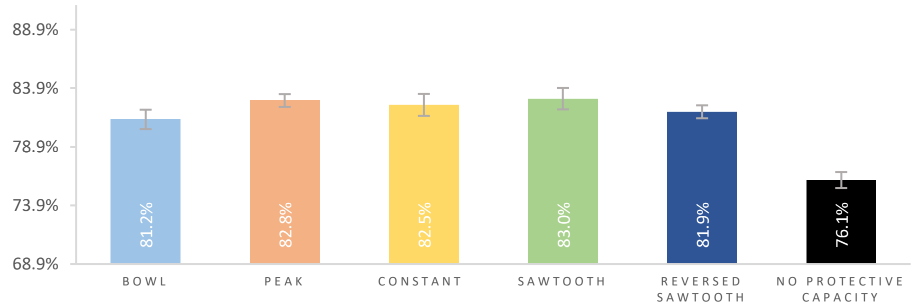

Figure 3.8: Experiment results equal reliability

In this figure it can be seen that the configurations in which protective capacity is added to the machines outperform the configuration without protective capacity and the base case. The peak ($p=0.002$), constant ($p=0.038$) and sawtooth shape ($p=0.005$) significantly outperform the bowl shape in this configuration. Furthermore, the peak shape significantly outperform the reversed sawtooth shape ($p=0.006$). Between the other shapes no significant difference exists.

One machine upstream less reliable: These experiments are performed again, however in this case the filling machine is made less reliable compared to the other machines to check if this makes a difference with the effectiveness of the different shapes. The results of these experiments can be seen in Figure 3.9.

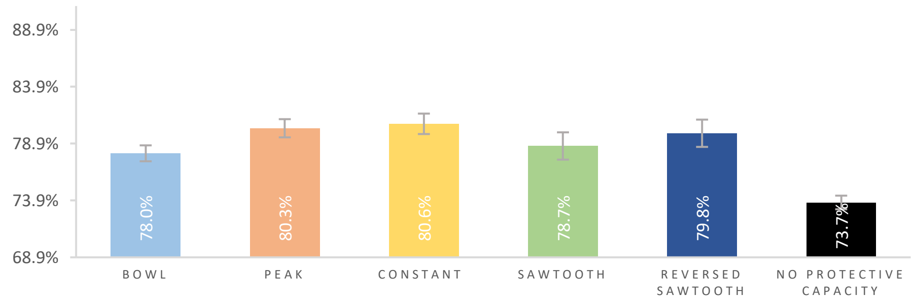

Figure 3.9: Experiment results upstream less reliable

The performance of the peak shape is significantly better compared to the bowl ($p=0.0002$) and sawtooth shape ($p=0.023$). Besides that, the constant shape is significantly outperforming the bowl shape ($p=6.89*10^{-6}$) and the sawtooth shape ($p=0.009$). All the shapes of protective capacity significantly improve the performance of the system compared to no protective capacity and the base case.

One machine downstream less reliable: The next experiment is carried out to check which shape is more effective when a machine downstream is less reliable than the other machines, in this case the packaging machine. The results of this experiment can be seen in Figure 3.10.

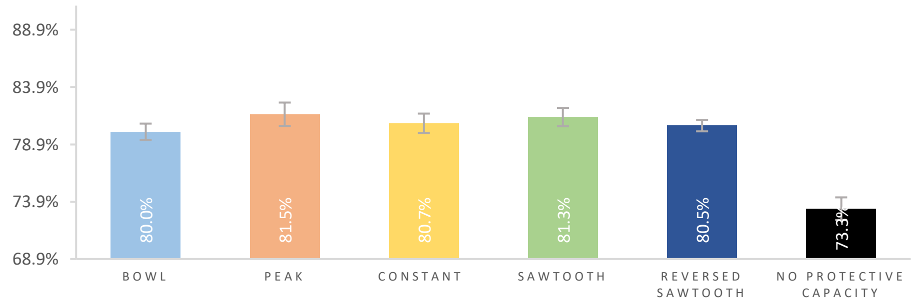

Figure 3.10: Experiment results downstream less reliable

It can be stated that there is a significant difference between having some sort of protective capacity in place compared to having no protective capacity and the base case. Besides that it can be concluded that the sawtooth shape (p=0.015) and the peak shape (p=0.012) are significantly giving a higher performance compared to the bowl shape in this configuration.

One machine in the middle most unreliable: The next experiment that is carried out, is the experiment in which a machine in the middle is the most unreliable, in this case the labelling machine. The results of this experiment can be seen in Figure 3.11 below.

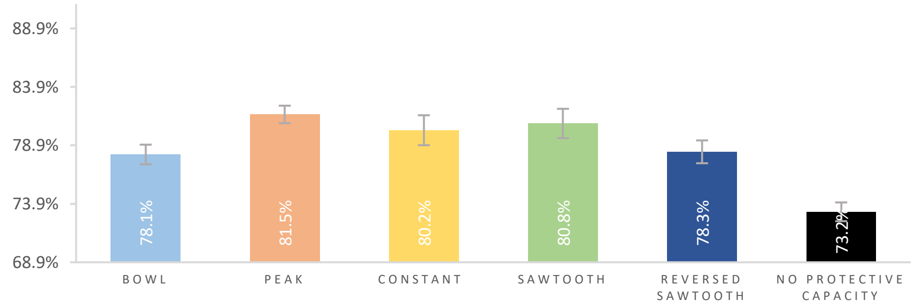

Figure 3.11: Experiment results middle less reliable

It can be said that the peak shape ($p=1.99*10^{-6}$), the constant shape (p=0.007) and the sawtooth shape (p=0.001) all have a significant higher performance compared to the bowl shape. These three shapes, the peak ($p=1.46*10^{-5}$), constant (p=0.018) and sawtooth (p=0.003) also perform significantly better compared to the reversed sawtooth shape. Between those three shapes itself there is no significant difference. There is again a significant difference between all the shapes of protective capacity compared to having no protective capacity at all and the base case.

The details of the results of the above carried out experiments can be found in Appendix B.2.

Amount of Protective Capacity

The experiments above have proven that the peak shape, the constant shape and the sawtooth shape in most case perform significantly better compared to the bowl shape and the reversed sawtooth shape. All five shapes are significantly performing better compared to having no protective capacity. For the three best performing shapes, the peak, sawtooth and constant shape, it is tested what the influence is when not 10% of protective capacity is added, but 5% or 15% for every machine. For the constant shape an extra capacity of either 10% or 30% is considered. For these experiments an equal reliability for all the machines is assumed. The results of these experiments can be seen in Figure 3.12.

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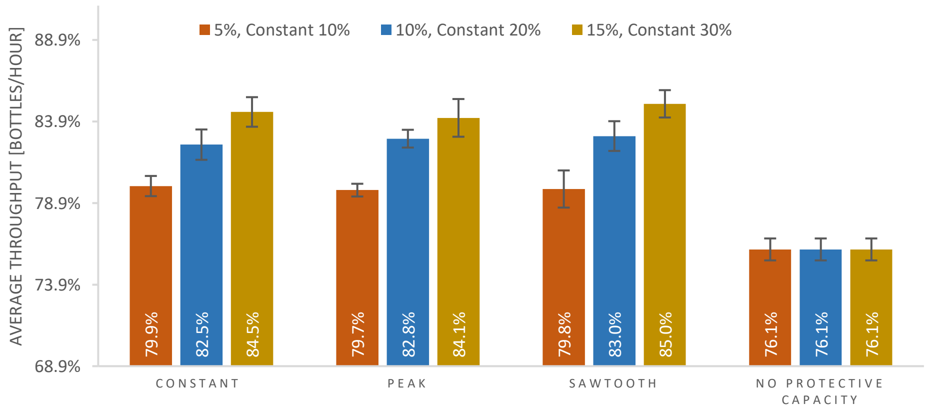

Figure 3.12: Results throughput experiments amount of protective capacity

From these experiments it can be seen that adding more protective capacity increases the performance of the system ($p=3.7*10^{-15}$ and $p=1.16*10^{-6}$). It is however more beneficial when the amount of protective capacity is increased from 5% to 10%, compared to increasing the amount of protective capacity from 10% to 15%. When the amount of protective capacity is increased even further, the amount of performance that can be gained by a step of 5% becomes less, up to when there exists no significant difference anymore when steps of 25% and 30% are used.

Furthermore, technical limitations of the machines and quality defects due to running at high processing speeds also need to be taken into consideration. Within every configuration there exists no significant difference in between the performance of the different shapes. However all the shapes in the different configurations perform significantly better than the performance without allocation of protective capacity.

The details of the above carried out experiments can be found in Appendix B.4.

Conclusion Protective Capacity

In Figure 3.13 below it is shown for each reliability configuration how many percentage of average performance is gained by each shape and adding 10% of protective capacity compared to the configuration in which no protective capacity is used.

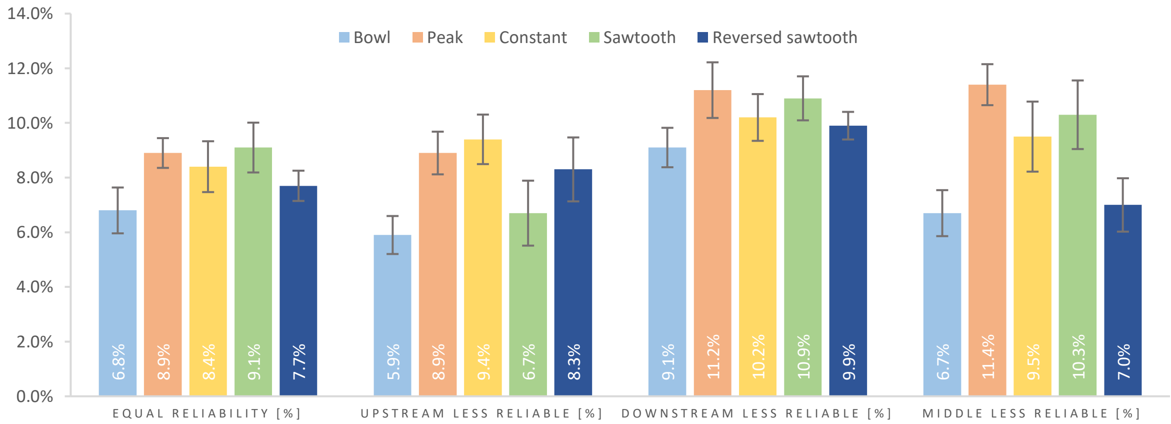

Figure 3.13: Percentage of performance gained compared to no protective capacity

From all these shapes the experiments above have proven that the peak shape, the constant shape and the sawtooth shape in most cases perform significantly better compared to the bowl shape and the reversed sawtooth shape. All five shapes are significantly performing better compared to no protective capacity and the base case.

In this figure it can also be seen that in the case when an upstream machine is less reliable it is harder to gain more productivity by adjusting the shape of the protective capacity. This was also seen earlier in the fact that an upstream machine being less reliable had the most effect on the total throughput of a production line. The most profit from adjusting the shape of the protective capacity can be gained whenever a machine at the end or the middle of a production line is the most unreliable, as can be seen in this table.

Furthermore, it can be concluded that it is better to have some sort of protective capacity assigned to the non-constraint machines, since these alternatives are performing better when machine are unreliable. In all four configurations the bowl shape and reversed sawtooth shape are performing the worst compared to the other shapes. This is quite remarkable since the bowl shape is used a lot in production lines, known as the "*V-shape*". However, when this shape is flipped and the peak shape is used, this usually gives the best performance, together with the constant and sawtooth shape. This can be explained due to the fact that when the machines closest to the bottleneck have more capacity, a blockage or starvation on the bottleneck machine will sooner be solved. Other circumstances can also influence the choice for the bowl shape. It can for example be that due to the technical limitations of the machines, the bowl shape is the only shape out of these five shapes that can be implemented on a production line.

Looking at the amount of protective capacity, it can be concluded that the performance of the system increases when more protective capacity is given to the machines. It however needs to be considered if this is technically possible for the machines and if it does not result in quality losses. For this reason the experiments in the following paragraphs are performed with an increase in protective capacity of 10%.

3.5.4 Experiments Buffer

All the above experiments were carried out with a buffer capacity of 2400 bottles. It would however be interesting to see what would happen if the amount of buffer capacity is changed. Furthermore, in the previous configurations it was assumed that the amount of protective capacity is activated all of the time. However, it might not be the most efficient for the machines with regard to degradation and quality losses to run at a high processing speed all of the time. For this reason it might be interesting to see what would happen with the performance of the system if the amount of protective capacity is activated at a certain fill level of the conveyor belts. The next paragraphs elaborate on these experiments.

Amount of Buffer Capacity: Small Buffer

The first experiment with regard to buffer capacity is performed for the case in which all the machines have an equal level of reliability and a small buffer capacity of 240 bottles in between the machines. These experiments resulted in the average performances that are displayed in Figure 3.14.

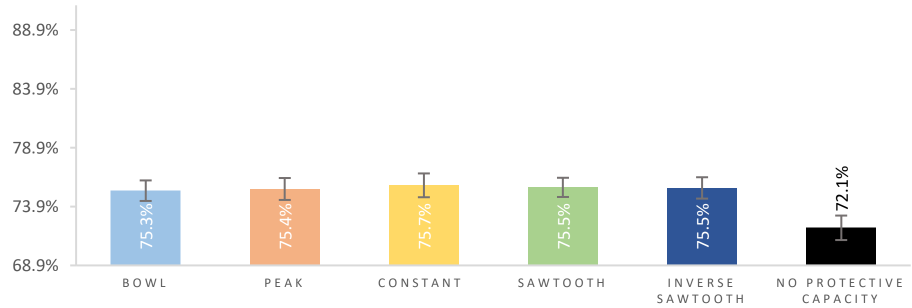

Figure 3.14: KPI's Performance experiment small buffer and equal reliability

From these experiments it can be concluded that there exists a significant difference in performance between a buffer of 240 bottles and 2400 bottles ($p=9.96*10^{-7}$). This experiment firstly makes clear that adding some amount of buffer capacity increases the performance of the system. Furthermore, it can be concluded that there is no significant difference with regard to the performance of the five different shapes. There is however a significant difference between the performance of the five different shapes compared to having no protective capacity in place and the base case.

To check if the same holds for other reliability configurations the same experiment with a very small buffer is carried out, including an extra unreliable machine upstream, downstream or in the middle. The results of these experiments can be seen in Figure 3.15 below.

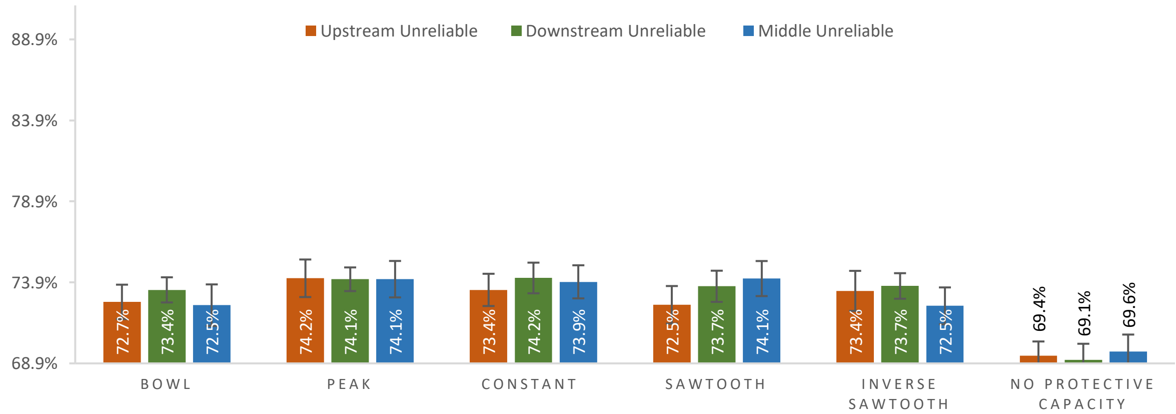

Figure 3.15: KPI's performance experiments small buffer and less reliable upstream and downstream

For an unreliable machine upstream the peak shape performs significantly better compared to the sawtooth shape (p=0.05). Between the other shapes no significant difference exists. Whenever the machine downstream is less reliable no significant difference between the shapes exists. However, when a machine in the middle is less reliable, the constant (p=0.042), peak (p=0.032) and sawtooth shape (p=0.026) significantly outperform the reversed sawtooth shape. The peak (p=0.047) and sawtooth shape (p=0.040) also perform significantly better compared to the bowl shape in this situation. In all three configurations there is a significant difference between no protective capacity and a form of protective capacity. Between having no protective capacity in place and the base case no significant difference exists. This can be explained by the fact that the only differences between these experiments is a buffer of 240 bottles instead of 48 bottles and another machines which is less reliable. From this it can be concluded that when the buffer is still relatively small, a small increase in buffer capacity does not increase the performance of the system.

Amount of Buffer Capacity: Large Buffer

Another experiment is carried out with machines having an equal reliability, however in this case very large buffers of 9600 bottles are added in between the machines, to see what the effect of a larger buffer would be on the preference for a certain shape. The results of these experiments can be seen in Figure 3.16 below.

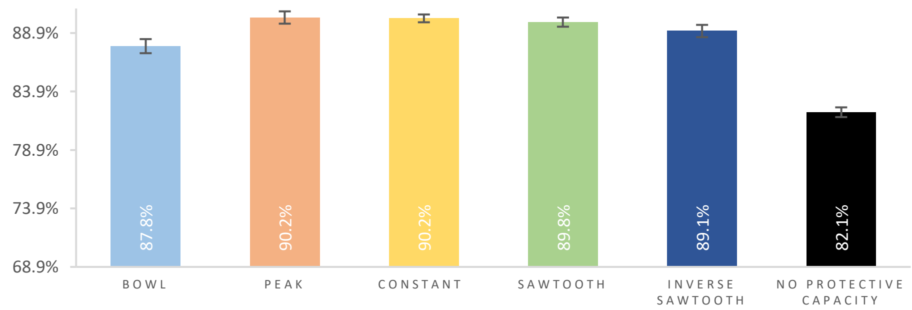

Figure 3.16: KPI's performance large buffers and equal reliability

From these experiments, it can be concluded that the performance of the system significantly increases when more buffer capacity is added in between the machines ($p=1.-7*10^{-12}$). This makes sense, since in this case the buffers are able to absorb more of the failures that occur on the machines. Furthermore, it can be concluded that all five shapes perform significantly better compared to having no protective capacity in place and the base case. Besides that, the bowl shape and the reversed sawtooth shape perform significantly worse than peak ($p=1.80*10^{-6}$ and p=0.002), constant ($p=3.58*10^{-7}$ and p=0.001) and sawtooth shape ($p=4.41*10^{-6}$ and p=0.017).

Adding extra buffer capacity in between the machines is however not always realistic, since in reality there is limited space to place these buffers and there are financial limitations. For this reason, it could be interesting to test at which place in the production line it is the most effective to place a larger buffer.

Placement of Buffer Capacity

These experiment are carried out only with the peak, constant and sawtooth shape of protective capacity, since these have proven to perform the best compared to the other shapes and this limits the amount of experiments. The alternative with no protective capacity is tested to compare the results with. The results of these experiments can be found in Figure 3.17.

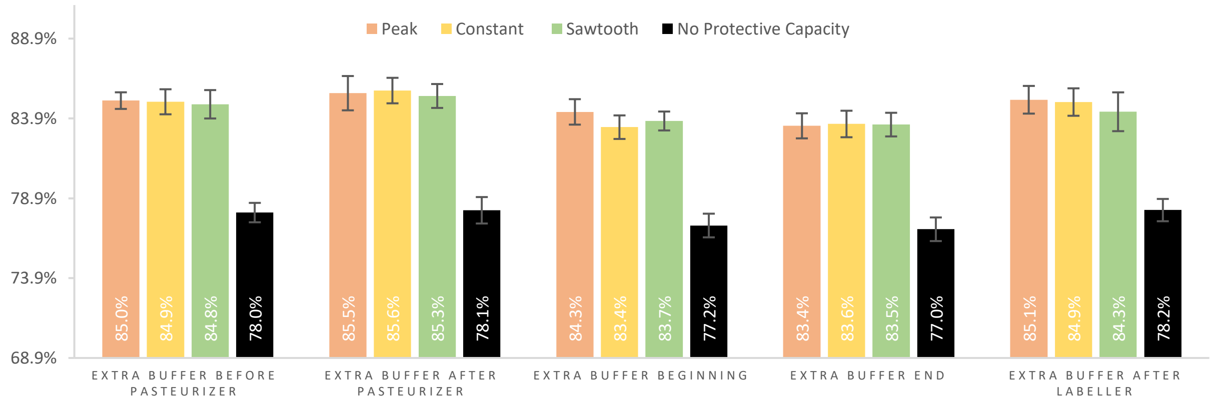

Figure 3.17: Results KPI Average Performance when one larger buffer is added [%]

From these experiments it follows that there is no significant difference between the peak, the constant and the sawtooth shape in all configurations. Besides that, adding the extra amount of buffer capacity before the bottleneck ($p=9.31*10^{-5}$ and $p=2.02*10^{-6}$), after the bottleneck ($p=3.25*10^{-7}$ and $p=7.75*10^{-9}$) or after the labelling machine ($p=0.007$ and $p=0.0002$) gives a significant better performance compared to extra capacity at the beginning or end of the production line. Adding extra capacity after the bottleneck performs significantly better compared to adding extra capacity after the labelling machine ($p=0.039$) or before the bottleneck machine ($p=0.05$).

These experiments were only carried out for machines with equal reliabilities, it can however be expected that whenever one machine is less reliable than the others, these results might change. To test if this is the case, the filling machine is made less reliable than the other machines and the experiments are repeated for this configuration. The results of these experiments can be seen in Figure 3.18 below.

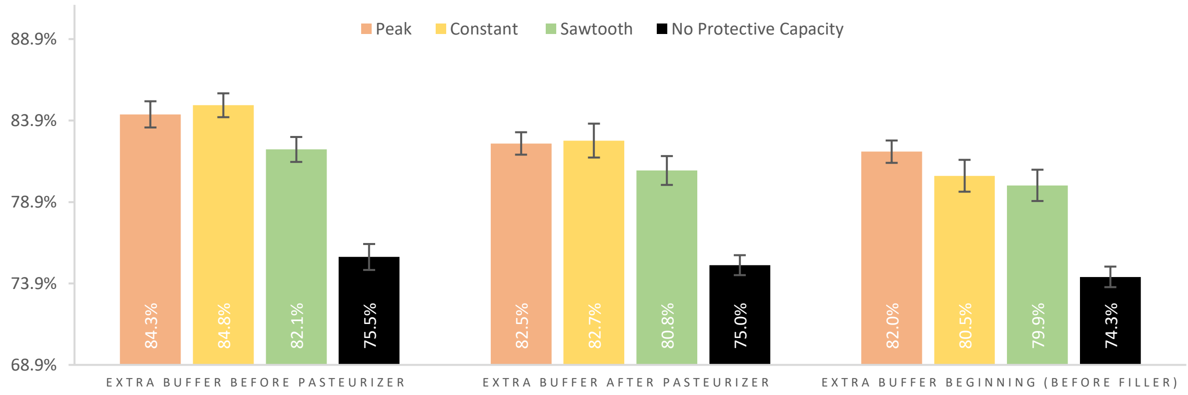

Figure 3.18: Results average performance of experiments placement extra buffer if filler is less reliable [%]

An extra larger buffer is in the case of this experiment significantly more productive when it is placed before the bottleneck machine instead of in front of the most unreliable machine ($p=0.0001$) or after the bottleneck ($p=0.001$). For this configuration the constant ($p=1.71*10^{-5}$) and peak shape ($p=0.0004$) significantly outperform the sawtooth shape. The fact that the configuration in which the extra buffer is placed before the bottleneck machines performs best can be explained by the fact that in this process the most unreliable machine is located directly in front of the bottleneck. This means that when the larger buffer is placed before the bottleneck and thus also after the most unreliable machine, it influences that machine by decreasing the chance that the bottleneck machine becomes starved.

To check if it is the same whenever the most unreliable machine is not located in front of the bottleneck, but at the end of the production line, the experiments are repeated and the packaging machine is assumed the most unreliable machine. The results of these experiments can be seen in Figure 3.19 below.

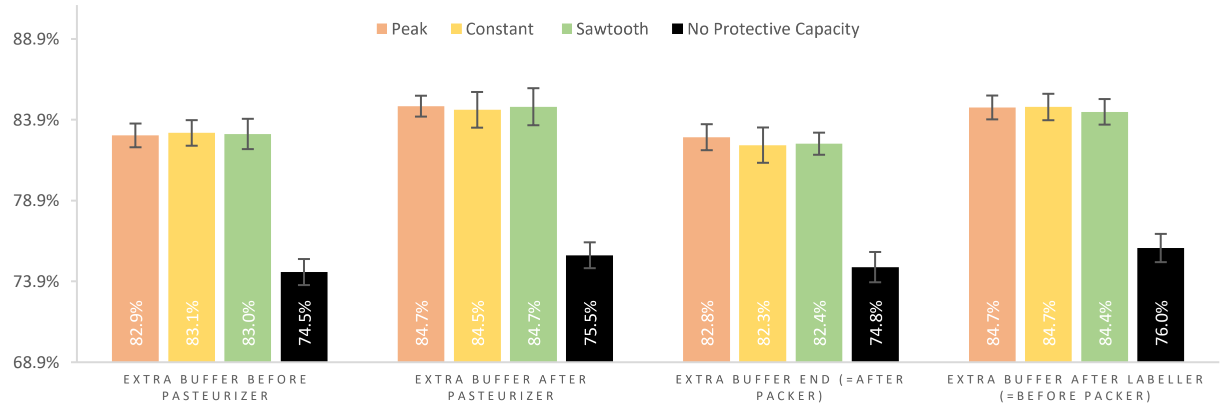

Figure 3.19: Results average performance of experiments placement extra buffer if packer is less reliable [%]

Between these three shapes of protective capacity there exists no significant difference. The two configurations of having either an extra buffer after the pasteurizer or before the most unreliable machine perform significantly better compared to having an extra buffer either after the most unreliable machine ($p=2.20*10^{-8}$ and $p=2.79*10^{-9}$) or in front of the bottleneck machine ($p=3.19*10^{-6}$ and $p=6.92*10^{-7}$). Between these two options no significant difference exists. The fact that these configurations result in the highest performance can be explained, because whenever a failure occurs downstream it influences the bottleneck by becoming blocked. When the buffer after the bottleneck is larger, this is less likely to occur. The same holds for a larger buffer directly in front of the most unreliable machine, this also decreases the chance of the bottleneck machine becoming blocked, whenever a failure occurs at the most unreliable machine.

Buffer Control

In the previous configurations it was assumed that the amount of protective capacity is activated all of the time. However, it might not be the most efficient for the machines with regard to degradation and quality losses to run at a high processing speed all of the time. For this reason it is investigated what the effect is when the protective capacity is activated at a certain fill level of the conveyor belts. For the conveyor belts upstream of the bottleneck machine it is ideal if the conveyor belts are always almost completely full. This means that whenever the conveyor belt is becoming emptier, a higher processing speed needs to be activated on the machine in front of the conveyor belt. If the buffer is completely filled again, the processing speed of the machine can be changed back to the nominal speed. For the machines downstream of the bottleneck the opposite applies. In the ideal situation these conveyor belts are always almost completely empty. This means that whenever a conveyor belt is becoming more occupied the processing speed of the machine after it needs to be increased. Once the buffer is almost completely emptied again, the machine can switch back to its nominal speed.

What the effect is of implementing such a switch is tested in the case of all machine being equal reliable and having a buffer capacity of 2400 bottles in between the machines. Upstream of the bottleneck four different configurations are assumed: activate the protective capacity at a fill level of 30%, 40% , 50% or 60% and downstream also four configurations are assumed: activate the protective capacity at a fill level of 70%, 60%, 50% or 40%. They are respectively combined together. The results of these experiments can be seen in Figure 3.20 below.

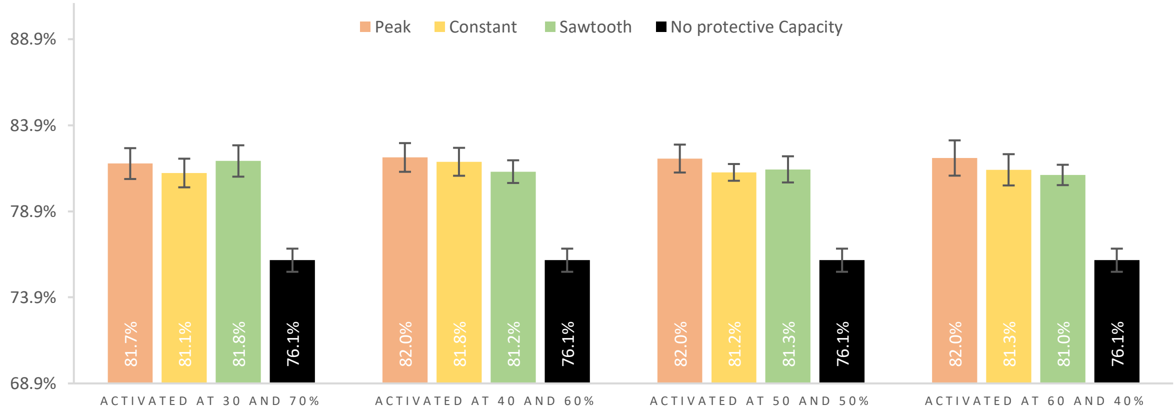

Figure 3.20: Results average performance experiments activation protective capacity, buffer of 2400 bottles

There exists no significant difference between the three shapes of protective capacity in these configurations. With regard to at which moment the buffer capacity should be allocated also no significant difference exist. This means that whenever a stoppage occurs probably the whole buffer is emptied or filled and in that case the protective capacity is activated in all the configurations. It can also be seen that some performance is lost due to not having the protective capacity activated all of the time. If this is however the case in reality is dependent on the fact how much extra quality losses running at the higher speed continuously results in. This is a consideration that needs to be taken into account when the system with regard to protective capacity will be installed in a production line.

Since there exists no significant difference between when the protective capacity needs to be activated for a medium buffer capacity of 2400 bottles, these experiments are repeated for a larger buffer of 9600 bottles in between the machines. The results of these experiments can be seen in Figure 3.22 below.

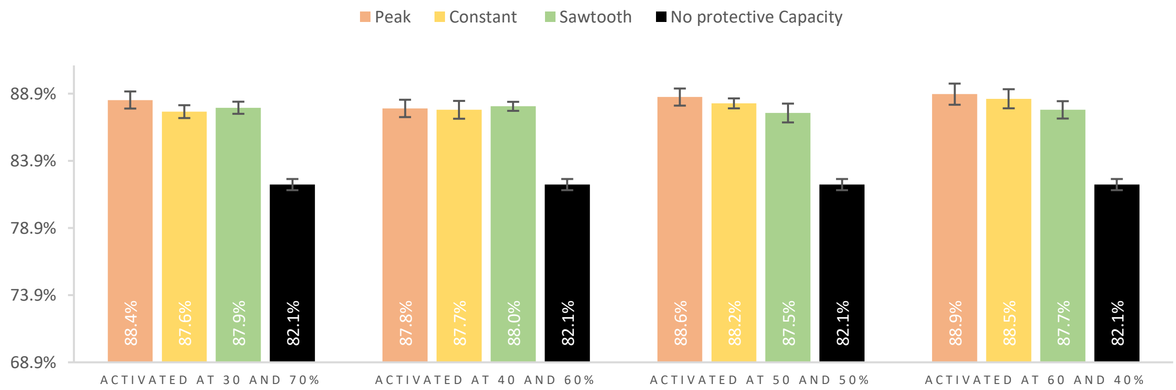

Figure 3.21: Results average performance experiments activation protective capacity, buffer of 9600 bottles

A significant preference can be seen for the peak shape compared to the constant shape (p=0.024) in the configuration in which the protective capacity is activated at 30% and 70% buffer level. In the configuration of a fill level of 40% and 60% there is no significant preference for a certain shape. However in the configuration of fill levels of 50% and 50% and 60% and 40% the peak shape performs significantly better compared to the sawtooth shape (p=0.011 and p=0.018). Looking at the preference for a certain fill level at which the protective capacity is activated, it can be stated that a significant better performance is given when the buffer level is activated at 50% and 50% (p=0.049) or 60% and 40% (p=0.03) compared to 40% and 60% when the peak shape is adapted at a production line. However, when a production line has adapted the constant shape, the 50% and 50% (p=0.034) or the 60% and 40% (p=0.021) configuration performance significantly better compared to activating the protective capacity at 30% and 70%. For the sawtooth shape no preference exists with regard to the moment at which the protective capacity is activated.

From this it can be concluded that in three out of the four configurations the peak shape outperforms the constant or sawtooth shape. And whenever this peak shape is chosen to be implemented at a production line it is better to active the protective capacity earlier when the buffer is becoming fuller or emptier to reach a higher performance. However, the impact this has on the quality of the product needs to be considered.

Conclusion Buffer Capacity

From the above carried out experiments some conclusions with regard to the performance in relationship with the amount of buffer capacity can be drawn. It can first of all be stated that whenever a relatively small buffer is placed in between the machines, this significantly decreases the performance compared to a large or medium sized buffer. When larger buffers are placed in between the machines this significantly improves the performance compared to having medium sized buffers.

However, placing a large buffer in between all the machines is not always possible. For this reason it is investigated at which place in the production line the largest buffer needs to be placed in relationship with the reliability pattern of the production line. From these experiments it can be concluded that whenever all machines are equally reliable it is best to place the larger buffer directly after the bottleneck machine. However, when the less reliable machine is located directly in front of the bottleneck machine, it is best to place the larger buffer in front of the bottleneck machine. Furthermore, when the less reliable machine is located at the end of the production line, the highest performance can be gained by placing the larger buffer either in front of the less reliable machine or directly after the bottleneck machine.

With regard to buffer control, it can first of all be stated that if the extra amount of protective capacity is activated at a certain fill level of the buffer this slightly decreases the performance of the system. However, this also means less quality defects, which need to be taken into consideration. For a buffer of 2400 bottles there is no significant difference between the various levels at which the extra protective capacity should be activated. However, when a large buffer of 9600 bottles is considered it is best to activate the protective capacity early on when the buffers are starting to become fuller or emptier compared to the ideal state, meaning at either 50% and 50% or 60% and 40%. The peak shape is preferred against the sawtooth shape in these two configurations.

3.6 Conclusions

From the experiments that were carried out with regard to the protective capacity and the buffer capacity of a one-way bottling and packaging production line, some general conclusions to improve the overall productivity of a production line are given.

First of all, it can be concluded that having protective capacity at the non-bottleneck machines gives a significant higher performance in all the configurations than having no protective capacity in place. Furthermore, the constant, peak and sawtooth shape have proven to give a significant higher performance in most situations. Which shape is the most effective, is however dependent on the reliability pattern of a production line and the buffer capacity that is present in between the machines. Increasing the amount of protective capacity that is assigned to the machines increases the performance. It should however be noted that running at a higher speed can also causes quality losses, due to faster wear and tear of the machines. This needs to be taken into consideration.

Secondly, with regard to the buffer capacity some conclusions are drawn. It can first of all be concluded that increasing the amount of buffer capacity improves the performance of the system. However, this is to a certain limit and increasing the buffer capacity everywhere in a production line will not always be possible. Where in the production line a larger buffer needs to be placed is dependent on the reliability pattern of the system. If all machines have an equal reliability it is best to place the extra buffer capacity directly after the bottleneck machine. However, when the most unreliable machine is located upstream of the bottleneck, the largest buffer can best be placed in front of the bottleneck. Finally, when the most unreliable machine is located downstream, the largest buffer can best be placed directly after the bottleneck or in front of the most unreliable machine.

Furthermore, it was checked at which fill level the amount of protective capacity can best be activated. Whenever a medium sized buffer is located in between the machines, no significant preference exists. However, when larger buffers are located in between the machines, it is best to activate the protective capacity earlier on when the buffers are starting to get fuller or emptier compared to their nominal fill level.

The above given conclusions are used to be applied to a situation from the field of practice. This situation is explained in chapter four and the improvements based on the above conclusions are given in chapter five.

3.7 Recommendations for the field of practice

Following from the above given conclusions some recommendations for the field of practice in which one-way bottling and packaging production lines are used, can be given.

First of all it is recommended for production companies to investigate, before installing a production line, what the bottleneck machine of that line will be. Based on that machine the protective capacity that needs to be allocated to the other machines can be determined. In which way this extra amount of protective capacity should be allocated is dependent on the reliability of the system.

For that reason it is recommended to investigate what the reliability of the machines which are part of the production line will be. Based on these properties of the production line it is advised to implement the shape that best fits with these properties, as was elaborated in the conclusion in the previous paragraph. This means that in most cases it is recommended for the field of practice to implement either the peak shape, constant shape or sawtooth shape to their production lines.

Once the reliability pattern of the production line is known, it is also recommended to base the placement of the conveyor belts and its corresponding buffers on this reliability. This means that the larger buffers should be placed according to what is suggested in the conclusions in paragraph 3.6.

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4 Case Study Line 52 Heineken Data Analysis

To analyse how the before derived results can be applied in the field of practice and how these can be used to improve the performance of a real life system, a case study is conducted at Heineken. This chapter focusses on the two inner levels of Heineken and production line 52 as was displayed in Figure 1.3. In this chapter the context in which the case study takes place is firstly elaborated in paragraph 4.1. In this paragraph the packaging department of Heineken at the location Zoeterwoude is elaborated, with special attention to production line 52. In the second paragraph it is explained what happens whenever machine failure occurs on this production line and what the effects and reasons for these failures are. In the third paragraph the data analysis of the available data from Heineken is conducted and the current performance of the production line is elaborated.

4.1 Heineken Zoeterwoude and packaging line 52

Heineken is the second biggest beer brewing company in the world (Heineken, 2019). Their biggest brewery in the Netherlands is located in Zoeterwoude. An image of the brewery itself can be seen in Figure 4.1. The brewery consists of five different departments, namely Packaging, Technology & Quality, Technical Service, Brewing and Safety, Health & Environment. For this thesis the focus is at the Packaging department, which is divided into five different areas. Each area is responsible for their own production lines. The way in which these lines are divided among the different areas can be seen in Figure 4.2.

Figure 4.1: Heineken brewery Zoeterwoude

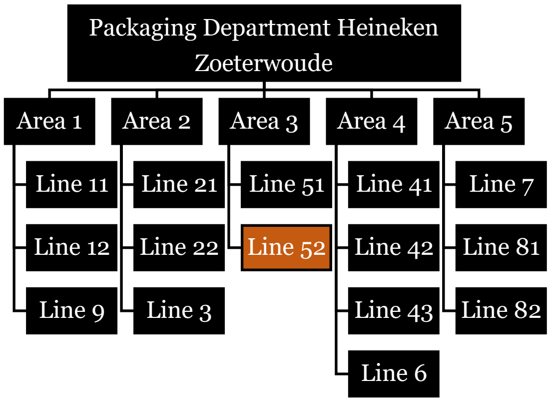

Figure 4.2: Packaging department Heineken Zoeterwoude

In Figure 4.2 it is shown that there are fifteen different production lines present in the brewery and each production area is responsible for two to four different lines. These production lines both fill and package beer in different kind of packaging materials, like for example crates and boxes with bottles, trays with cans, kegs and other materials. Each area has a responsible area manager, a production coordinator, an installation manager and multiple production team leaders. Those team leaders coordinate the operators, who can be divided in process control operators, specialist operators and all-round operators. These operators are responsible to keep the line working and for example take care of the fact that enough material is available, the machines keep operating, small errors are solved, check whether the right material is being used, perform small maintenance and cleaning tasks and contact the right people when a big error occurs.

Some of these production lines are running continuously and some of them have certain days on which they do not produce. This is dependent on the demand of the kind of product the lines produce. Besides that, all the lines have certain stop-days on which they do not produce. These days are necessary to clean the line and to perform maintenance tasks.

For this thesis the focus is on production line 52. This line packages the beer in bottles, which are in their place packaged in carton boxes. These boxes are all destined for export, which mostly goes to the United States of America. This line only produces during the weekdays, which means that in the weekend the line is not working and no people are present at the production line. After the production has stopped in the weekend, every other week the Monday is used as a stop-day, which means that during this day the machines get maintenance and get cleaned. After a stop-day the production starts again at the end of the day on Monday and is stopped again on the night of Friday to Saturday. This means that during the week people are present at the line all the time.

On this production line several steps are taken to get from brewed beer to beer ready for export. This production line follows a similar process as the generic one-way bottling and packaging that was elaborated in the second chapter. The details of the machines that are part of the bottling and packaging process that is being conducted by production line 52 are elaborated in Appendix E.

4.2 Machine Failure

The machines that are part of production line 52 can experience failure due to multiple reasons. These failures can mainly be categorised in two categories. First of all the shorter stoppages, these stoppages influence only the machine on which the failure occurs and some surrounding machines. In this case the production line as a whole continues running. On the other hand, are the larger breakdowns, in which case the production line as a whole stops working due to this failure. Employees besides the operators present at the line are necessary to solve these breakdowns. Since the stoppages in the last category are usually breakdowns for which the root cause for every breakdown needs to be analysed individually to be prevented in the future, they cannot be eliminated or reduced by changing the properties of the system, since these are more of a technical nature. For this reason the choice is made for this thesis to focus only on the shorter failures, which are usually more of a chronic nature and its effects can be reduced by changing system properties.

Whenever such a stoppage occurs at the production line, the sign on top of the machine changes to a red colour to report to the operators on the line that the machine has stopped working and action is required. Whenever this is noted by an operator or an operator is available, he or she will walk to the machine and solve the error. This is usually done by restarting the machines or performing a small adjustment. After this has been done the machine can start working again.

4.2.1 Effect of stoppages on the buffer level

These stoppages can have effect on the other machines of the production line and on the buffer that is placed in between these machines. The conveyor belts that are located in between the machines can be divided in a part that is always occupied for transportation purposes and a part of the belt that can be used as a buffer and will in some situations not always be occupied. In order to reduce the effects of stoppages, Heineken has placed sensors at the buffers that determine the fill level of the buffer. Whenever these sensors notice that a buffer is filled to a certain level or if the buffer is too empty, the speed of the machines is respectively slowed down or if possible increased. This means that the buffer quicker restores to the nominal buffer level than whenever the machines keep running at the speed they are originally set at. How this principle works was explained in the second chapter. The points at which these sensors are activated and to which speeds the machines are set to operate, is further elaborated in paragraph 4.4 with regard to data analysis.

Furthermore, if the amount of blockage and starvation of the individual machines of production line 52 is investigated, it can be seen that the machines upstream of the bottleneck, the pasteurizer, experience more blockage compared to starvation. This can be explained by the fact that the machines downstream cause more blockage due to failure on the upstream machines. The opposite holds for the machines downstream, which experience more starvation compared to blockage. It is dependent on these capacities how much influence a stoppage has on the total availability of the production line. The allocation of the capacities of the machines are shaped like two bowls. This means that the above described allocation in the bowl shape is used at production line 52. It is shaped like two bowls, because at the case packer two different conveyor belts come together, which are transporting the boxes and the bottles.

4.2.2 Causes of Failures

The failures that occur at production line 52 have happened for different reasons. The most common reasons of failure for each machine at production line 52 were investigated. For this purpose a diagram is created. In this diagram it is displayed for every machine which percentage of the total failures is caused by which cause. The percentage one machine contributes to the total amount of failures on the production line is displayed in this diagram as well. The data that is used to create the figure is the data that is available over the time period from January 2019 to August 2019. The diagram is displayed in Appendix M.

The data that is used to create this diagram is measured by the Programmable Logic Controllers (PLC's), which are the computers that control the machines on the production line. These computers automatically record the cause for a failure. To create the diagram the data that is collected from January 2019 until August 2019 is used. The data that is collected in this period from the PLC can be derived from a database. This database shows the frequency of failure causes that can be registered by the PLC's. From this database, it is collected which failures can occur at every individual machine and how often each failure occurs. These failures are sorted from most occurring to least occurring. From this it could be concluded which failures occur most often on every machine. To calculate the percentages that are displayed in the figure the frequency of a failure cause is collected for each machine and divided by the total amount of failures a machine has experienced during the period. Following from this it could be seen for every machine what the most occurring causes of failure are.

In the case of some machines a lot of the reasons behind these failures are unfortunately unknown. For some of the machines some of the biggest reasons for failure are clear. For each machine it is also displayed which percentage of the total failures are caused by which machines. This percentage makes clear which machines are causing the most disruptions in the production process.

Looking at these causes of failure, it is of importance to investigate what the effects of these causes are. For most of the causes in the diagram the effect is that a machine stops working for a small period of time, because action from an operator is required. When for example a door is open, this needs to be closed before the process can continue. For other causes of failures, like for example a fallen bottle or wet carton, the items need to be removed from the machine or conveyor belt to be able to continue the process. Once it is known which machines are causing the most failures, the strategy with regard to maintenance can be focused on these causes. This is related to the target values that can be set for each machine with regard to the mean time to repair and the mean time between failures which is elaborated at the end of this chapter in paragraph 4.5.

This diagram can be very useful for manufacturing companies. This is due to multiple reasons. First of all, an insight in the reasons behind failures is very importance since in that way it can be known which failures are critical to the performance of a system. Secondly, once it is known which causes of failure are the most influencing, proper actions can be taken based on that. In this way manufacturing companies can increase the performance of their production lines.

4.3 Current KPI Performance of the System

Besides the before mentioned aspects of production line 52, also the current KPI of the performance of the system as was defined in the second chapter needs to be known. This is based on the total throughput of the system. The results of the calculations for each week of January 2019 – August 2019 with regard to the KPI of performance for production line 52 of Heineken are shown in Appendix F.

It can be seen that a lot of fluctuation exists in the performance of the system per week. This means there exists a lot of variability in the reliability of the machines and the system. Besides that, this can also be caused due to external influences, which are outside of the scope of this thesis.

4.4 Data Analysis

To perform the case study and build a simulation model of production line 52, certain information is necessary in the form of the concepts that were explained in the second chapter. First of all, data with regard to the reliability of the machines on production line 52 is needed. With regard to that, an excel file is available in which for each machine could be seen when it was processing, in failure, blocked or starved. For the purpose of this thesis it is chosen to only consider stops that are equal to or shorter than ten minutes. This has been chosen because, looking at the month July in 2019 as an example, 95.64% of all stoppages lasts shorter than ten minutes. For this reason, and for the reason that long stoppages affect the total production line in the sense that all the machines become blocked, it is chosen to only analyse stops that last shorter than ten minutes.

4.4.1 Machines

With regard to the machines, data of two categories needed to be gathered. First of all the reliability of the machines. This is expressed in a mean time between failures and a mean time to repair. Secondly, the processing times of the machines. Which data is used with regard to these two categories is explained in the next two paragraphs.

Reliability: Mean Time Between Failures and Mean Time to Repair
The time between the stoppages is collected for a period of seven months, starting on January 2019 and ending on August 2019. For the duration of the stoppages, also known as the mean time to repair, all the data on the stops lasting shorter than 10 minutes has been collected and a distribution over this data is gathered, these distributions are explained in Appendix H.1. For the time between these stoppages also data has been gathered for this period of time. From this data distributions are formed which are displayed in Appendix H.2 in more detail. The mean time to repair and the mean time between failures for the different machines can also be seen in Appendix H.

Processing Times
Besides the reliability of the machines also the processing times of the machines need to be known. Some of the machines used at production line 52 have a fixed speed, meaning that the machines is always set to process at the same speed. Other machines are able to switch to a faster speed, when for example the machine was starved before and it needs to catch up to replenish a buffer faster. These capacities can be seen in Appendix H.3. It should be noted that, in case of a full buffer in front of the machines, the machine can switch to a lower speed than the nominal speed that is noted in the table below.

4.4.2 Conveyor Belts

Next to the machines, it is also necessary to collect data with regard to the conveyor belts that are part of the system. This is data regarding the buffer and transportation capacity of the conveyor belts and the transportation time of the conveyor belts. The data that is collected with regard to these categories is elaborated below.

Capacity Conveyor Belts
First of all, the capacity, expressed in number of bottles, of the conveyor belts between the machines needed to be known. These numbers are displayed in Appendix H.4. Some of these buffers were measured by Heineken on multiple occasions and an average of these measurements is taken as the amount of available buffer capacity. Other buffer capacities were not known beforehand and they needed to be determined in consultation with operators on the line and with measurements.

Transportation Capacity and Buffer Capacity

The machines do not continue running until the total conveyor belt has been emptied or completely filled. Instead the machine gets a signal when the amount of bottles left on the conveyor belt has reached a certain level and are stopped automatically. This amount of bottles that is left on the conveyor belt is equal to the transportation part of the conveyor belts. These numbers were not known beforehand. To investigate how many bottles this are, the number counter on the machine was set to zero whenever the bottles have reached this point. From that moment the machine was set to start processing again until it has emptied the total conveyor belt. Once this has happened, the number counter was read again. This number is equal to the transportation part of the conveyor belt and is displayed in Appendix H.4 for every conveyor belt.

Following from these numbers, the buffer capacity of the conveyor belts can be calculated by subtracting the transportation capacity from the conveyor belt capacity.

Transportation Times

Besides the capacities of the conveyor belts, also the transportation time of these belts need to be known. This is the time it takes for a bottle to travel from one machine to another machine. These numbers were not known beforehand. To investigate what the transportation times are, a bottle was labelled once it exited a machine. From that moment on a stopwatch was started and the time it took to travel to the next machine was tracked. This resulted in the transportation times that can be seen in Appendix H.5. These transportation times can be used for the validation of the simulation model in a later stage.

Buffer levels at which the speed is changed

Appendix H.6 displays at which buffer levels of the conveyor belt the processing speed of the machines is changed. These numbers are based on the sensors that are located on the conveyor belts and layout that is available of these conveyor belts.

4.5 Buffer Time and Recovery Time

From the previously gathered data, it follows that some machines of the production line have a high failure rate. For this reason it is worthwhile to investigate for a production line which machines need the most attention with regard to maintenance to increase the reliability of the system. This can be done based on the buffer times and the replenishment and depletion times of the conveyor belts. The buffer time is the time a buffer can temporarily store the bottles before another machine upstream or downstream of the failing machine gets affected by the stoppage. The replenishment time is the time it takes after a stoppage and starvation until the buffer upstream is replenished to the nominal fill level again. The same holds for the depletion time, this is the time it takes after a failure and blockage until the buffer downstream is depleted to the nominal fill level again.

With regard to the buffer time the goal can be set for a production line to have the mean time to repair of a failure below this rate. The same holds for the replenishment and depletion time, but compared to the mean time between failures. The goal is to have the buffer restored to the nominal level again before another stoppages occurs, as was explained in the second chapter of this thesis.

4.5.1 Buffer Time

From the above derived data, it can be calculated what the theoretical buffer times are, as was explained in chapter two. This can be done looking at the buffer capacity and the speed of the machine that is in operation during a failure. To calculate the buffer time the buffer capacity should be divided by the speed of the operating machine. For a machine upstream of the bottleneck machine, the pasteurizer, this is the speed to which the machine is set to operate whenever the buffer between these two machines is becoming emptier. The buffer is seen as the amount of bottles that fit on the conveyor belt minus the amount of bottles that are left on the conveyor belt when a machine is automatically stopped due to starvation. The machines and their theoretical buffer times can be seen in Appendix G. For these machines downstream of the bottleneck, the theoretical buffer time is calculated in the same way as for the upstream machines, only in this case the machines do not stop because of starvation, but because of blockage.

This is however not the case for the conveyor belt in between the case erectors and the case packers, since at this point two different conveyor belts come together.

These buffer times can be compared with the current MTTR of the machines. This is the average amount of time a stoppage on these machines lasts. It should be avoided that a stoppage takes longer than the theoretical buffer time, because in that case the stoppage influences other machines. Beside the theoretical buffer time, also the actual buffer time can be compared to the MTTR. The actual buffer time is calculated by looking at the actual time that is between a failure on one machine and either blockage or starvation on another machine. This data is derived from the file in which it could be seen for every machine when it was either producing, starved, blocked or experiencing a failure. The comparison of these three values can be seen in Appendix G.

4.5.2 Replenishment and Depletion Time

The before mentioned causes of failures are usually caused due to a lack of maintenance or some errors in the properties of the system. Some machines contribute more to this than others. For this reason it is important to determine a target value for the amount of stoppages that should be allowed before action needs to be taken. This target is based on the depletion and replenishment time of the buffers.

For the machines that are part of production line 52, the buffer capacity and processing speeds of the machines need to be known. These times were given at the start of this paragraph and can be used to calculate the replenishment and depletion times. The results of these calculations are shown in Appendix G.

Based on these values it can be seen which machines need attention with regard to eliminating the causes of these stoppages to increase the mean time between failures and in this way more easily meet the target values. This increases the reliability and performance of the system.

4.6 Conclusion

Based on the before performed analysis it can be concluded which the critical areas of the production line are. These are areas in which the amount of protective capacity, the reliability of the machines and the amount of buffer capacity are low and for that reason the buffer time and recovery time targets are not met on most of these machines.

First of all this is the area around the bottleneck machine, meaning the filling machines and the CPL's. This area is first of all critical since the bottleneck is located here. Furthermore, the machines around the bottleneck experience a failure about one time each hour. A failure on one of these two machines does probably also starve or block the bottleneck machine since a relatively small buffer is located in between these machines. Furthermore, the processing capacities of both these machines are not a lot higher than the processing speed of the bottleneck machine. This makes this a critical area for which it is desirable to improve the performance. The fact that this is a critical area can also be seen in the buffer time and recovery time of these machines. When these are compared to the mean time to repair and the mean time between failures respectively they mostly do not meet these target values.

The second critical area is the area in which the bottles are packaged in boxes. This area is critical since the machines that are located here experience a lot of failures and the buffers that are located in between the machines are relatively small. However, the machines that are located here are further away from the bottleneck and have higher processing speeds. This means that the influence of these machines on the total performance of the system is less compared to the machines close to the bottleneck. But due to the low reliability of these machines they do decrease the performance of the system and are thus of importance to be improved. The criticality of this area can also be seen in the buffer time and recovery times of these machines. The mean time to repair and mean time between failures do often not meet these target values.

5 Case Study Line 52 Heineken Improving Productivity

Looking at the current performance of production line 52, as was elaborated in the fourth chapter, some improvement alternatives are suggested based on the results of the generic model as is given in chapter three. In the first paragraph the conceptual model that is created of the existing production line 52 is explained together with the simulation model, which is based on this conceptual model. In the second paragraph the experiments that are carried out to test the different alternatives are elaborated and the results of these experiments are discussed. In the fourth paragraph a conclusion with regard to this chapter is given. Finally, this conclusion is translated into an implementation plan for Heineken to improve the productivity of the production line in the fifth paragraph.

5.1 Conceptual model of production line 52

Production line 52 is seen as a specification and detail variant of the generic model that was used in the third chapter. In this model more details with regard to the machines which are present at the production line are known and added to the model. With the use of this model it can be seen how the improvement alternatives that were suggested in the third chapter apply in the field of practice.

To model the system of production line 52 which was described in chapter four, some assumptions need to be made. These assumptions are explained below.

5.1.1 Assumptions

In this paragraph the assumptions that are made to form the conceptual model are explained. These assumptions are necessary to simplify the reality and make the model more workable.

Short stoppages
As was explained before, in this thesis only the short stoppages that last less than ten minutes are taken into account. This has been chosen because the effects of these stoppages, blockage and starvation, can be reduced by changing the properties of the system.

Small buffers between machines
First of all, some machines are located very close to other machines, for example the de-foiling machine and the depalletiser, the case erector and the interior placer and the palletiser and the foil machine. For these machines it is chosen to model them as one "big machine". These machines cannot differentiate in the processing speeds to recover a buffer faster, because almost no buffer is present in between these machines.

Operators
It is difficult to model the operators in the simulation model, because the data does not allow for that. The data that is available for the duration of the stoppages include the time that it takes for the operators to react on a stoppage, to finish what they are doing and to walk to the machine. It is known that sometimes a stoppage lasts longer because an operator reacts later on a sign, is busy with something else or maybe is not present at all. It is however not known which percentage of the mean time to repair is reaction time. For this reason it is chosen not to include this aspect in the conceptual model.

Conveyor speed and length
The conveyor speed is assumed to be equal to the highest processing time of the machines to which it is connected. Furthermore, the length of the conveyor is assumed based on the amount of bottles that can fit on the conveyor belt.

First and last machine of the production line

Another assumption that is made is that the first machine of the line is never starved of equipment and the last machine of the line always has place to put its processed material. In reality it can happen that the department that is responsible for the brewing of the beer or the supply of the material also has some failures and for that reason they cannot supply the equipment to the production line. The same can happen at the end of the production line if there is no place in the storage to put the materials or the machines used for storing the pallets is broken. Because these are external factors, they are outside the scope of this thesis and the assumption is made that these problems do not occur.

Start-up periods, adjustments and planned stoppages

For this thesis the start-up periods, adjustments and planned stoppages are not taken into account since the behaviour of the system is studied whenever this is in a steady state.

Rejection of bottles

Bottles are being rejected at multiple points at the production line. This is however not a very big percentage, around two percent of the total production. In this conceptual model it is assumed that no bottles are being rejected.

5.1.2 Simulation model of production line 52

To be able to apply the improvement alternatives of chapter three, a more detailed simulation model of the production line needed to be created. The processing times that were given in Appendix H are used, the distributions for the reliability as are given in Appendix H are assigned to the machines and the buffer capacities as were given the previous chapter, are used for the conveyor belts. The conveyor speed is set so that it could handle all the material that is put on it.

For the first machine of the production line, the depalletiser use is made of a *Separator*. This is the opposite to the *Combiner* as was used in chapter three. The properties that can be assigned to a separator can be seen in Appendix B. A new pallet is sent into the process once the depalletiser has finished processing one pallet. Once the bottles are removed from the pallet, the pallet is destroyed by the *Sink* and the bottles are placed on the conveyor belt that moves them to the filling machines.

The filling machines are modelled as a *Server* that can change to a lower speed when the buffer level has reached a certain value as was explained in the previous paragraph. This is done using an add-on process that is displayed in Figure 5.1. In this process it is first decided if the buffer level is according to the nominal fill level, if this is the case the nominal processing speed is assigned to the machine. When this is not the case it is checked if the buffer level is at the level at which the processing speed of the machine needs to be changed. If this is the case, the catch-up speed is assigned to the machine. At which buffer levels this happens was displayed in Appendix G. After that, it is checked if the buffer level is at the nominal fill level again and the processing speed of the machine is changed back to the nominal speed.

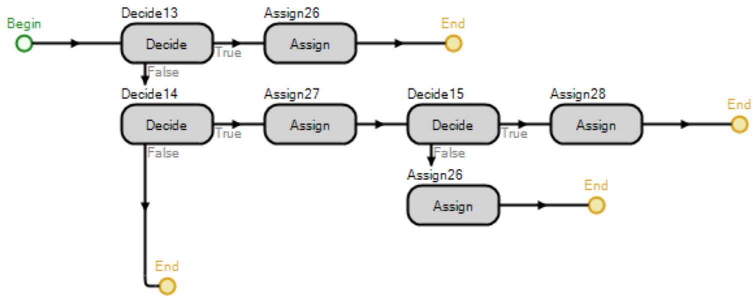

Figure 5.1: Add-on Process Buffer Control

Once the bottles are processed by the filling machines, they are moved onto the next conveyor belt that transports them to the pasteurizer. This conveyor belt exists out of two parts that come together. The pasteurizer is modelled as a series of eight large conveyor belts. The conveyor belts start and end in a *Server* that controls the amount of bottles that are put on and removed from the eight conveyor belts. It has been chosen to model the pasteurizer in this way since a lot of bottles travel through this machine at the same time for a period of approximately fifty minutes. Once the bottles have gone through the process of the pasteurizer they are put on the next conveyor belt that transports them to the CPL's. Both CPL's are modelled as a *Server* and for the catch-up speed and lower speed of the machines the add-on process as was displayed in Figure 5.1 is used. Once the bottles have been processed by the CPL's they move onto the next conveyor belt that exists out of six different parts.

At the same time the case erectors, which are both modelled as a *Server,* are sending boxes into the process. Once a box has been processed by the case erectors, a new box is sent into the process. At the packaging machines two conveyor belts come together. The two packaging machines are each modelled as a *Combiner,* which combines 24 bottles with one box. For the packaging machines, the add-on process as was displayed in Figure 5.1 is assigned for the catch-up speed of these machines.

Once the bottles are combined with the boxes, they are moved onto the next conveyor belt. Once the boxes have travelled this belt, they arrive at the case closers which are modelled as a *Server.* After the boxes are processed by the case closers, they are moved onto the final conveyor belt that consists out of three parts. This conveyor belt moves the boxes to the palletiser that is modelled as a *Combiner.* The palletiser combines multiple boxes onto one pallet. Once this has happened the process is finished and the pallets are destroyed by the *Sink.*

This resulted in the model which is shown in Figure 5.2. This model is a specification from the more abstract model that was used in chapter three and was displayed in Figure 3.7. Compared to this model more detail is added to the simulation model of production line 52. Consequently, the simulation model of production line 52 needs to be verified again.

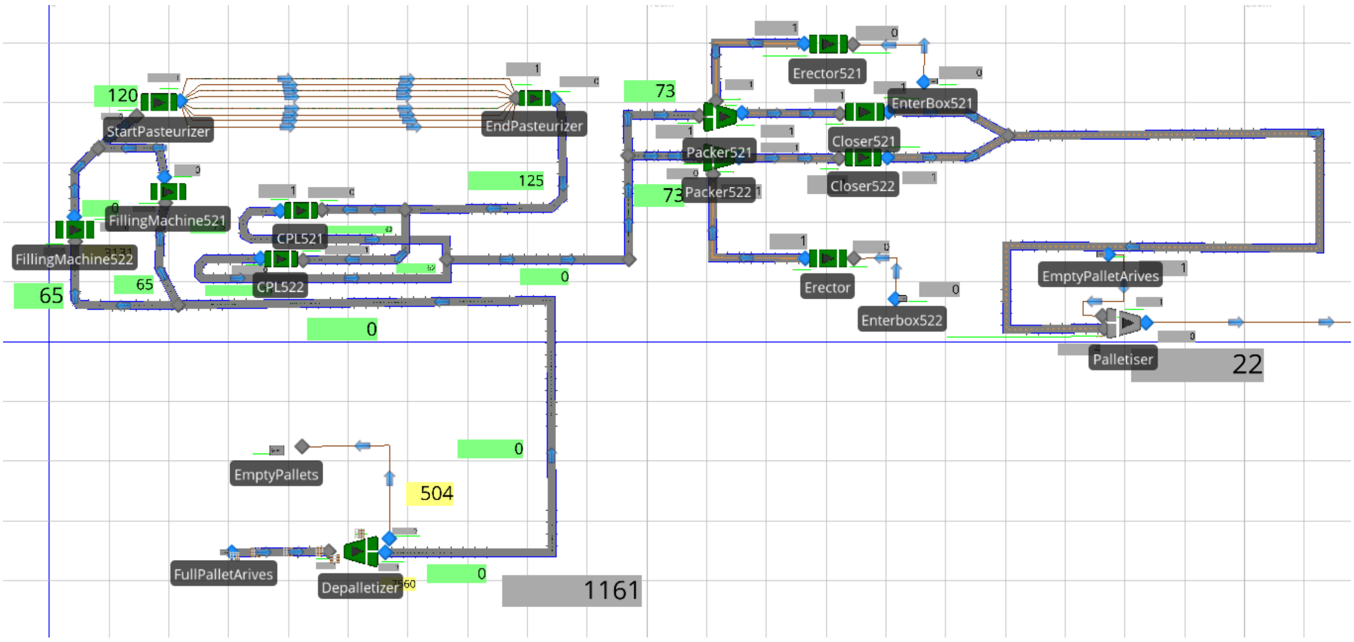

Figure 5.2: Basis simulation model of production line 52 Heineken

This model represents the current situation at which the production line is performing. To check if this is the case the model should be validated and verified. This is done in the next paragraphs.

5.1.3 Verification of the simulation model

The assumptions above are all taken into account when the simulation model of the production line was created. This simulation model is a more detailed model of the simulation model that has been used in the third chapter. The first detail which is added is the fact that the machines of production line 52 are modelled as parallel machines. To verification if these parallel machines work according to how it is expected in the model, the model was firstly verified with a sample experiment. In this experiment the capacities of the machines are set at 80,000 bottles per hour and 40,000 bottles per hour for the parallel machines respectively. Once this experiment was run, it was checked if the throughput of the system was indeed 80,000 bottles per hour. This could be confirmed.

Afterwards, the model was extended to the model as is displayed above. In comparison with the generic model from chapter three, the pasteurizer has been extended and case erectors and closers have been added. For this model it is checked if the model is working accordingly to how it is expected. To verify the model, labels are added that check if the properties of the model perform according to what should be expected. To verify if the buffer control is working accordingly, labels are added that track the processing time of the machine and the buffer level.

From this it follows that indeed the higher processing time for a full buffer is activated whenever the buffer reaches a the maximum value that can fit on the belt. Whenever the buffer level is decreasing again, the processing capacity is indeed turned back to its nominal speed. The processing times of all the other machines of the production line are checked to see if they operate at the right speed. The same is done for the capacities of the conveyor belts. For these belts it is checked if the amount of bottles or boxes that should be able to fit on them are not exceeded. This can indeed be confirmed.

From these steps that are taken to verify the model, it can be stated that the model is indeed behaving as is expected and the model can be verified.

5.1.4 Validation of the simulation model

Once the model has been verified, the next step is to validate the model. This means that it needs to be checked if the model is behaving according to the situation of production line 52 which can be seen in reality.

Performance Validation

In the performance validation the performance of the simulation model needs to be compared to the performance of the real system. To do so, historical data with regard to the performance of the system is used as was given in paragraph 4.3.4.

To check how this compares to the situation in the field of practice an experiment with the current model is performed. The results of these experiments are displayed in Table 5.1 and Figure 5.3 below.

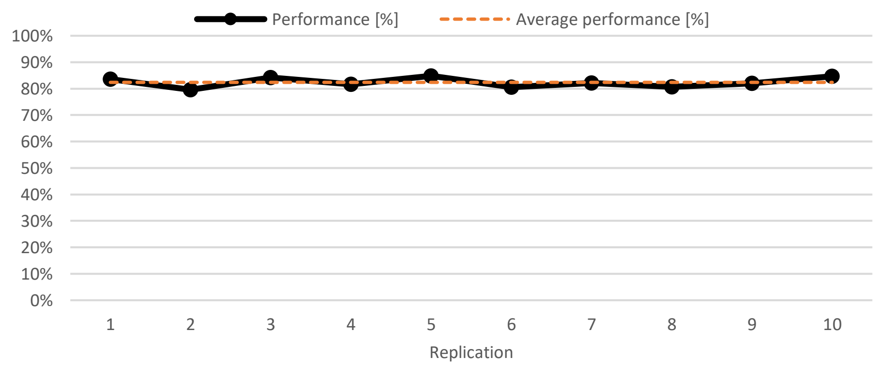

Figure 5.3: Performance of replications simulation model line 52

Table 5.1: Verification simulation model line 52 Heineken

Average throughput [bottes/hour]	65906
Average operation time [hours/24 hours]	19.8
Average performance [%]	82.4%

From these numbers it can be concluded that the production line is not producing all of the time, since the performance of the system is below one hundred percent and the throughput below the maximum of 80,000 bottles per hour. However, when these numbers are compared with the numbers from reality. However, this can be explained due to multiple reasons. First of all, in the simulation model only the short stoppages are taken into account. Secondly, quality rejects are not considered in the scope of this thesis. The left difference can be explained by the fact that in the simulation model it is assumed that losses which are caused due to start-up of machines, the adjustment of machines and losses which are caused by external causes, like for example different departments, are not taken into account. The exact numbers that were used for this verification are displayed in Appendix N.

The expectation is that the differences that can be seen between the simulation model and the real life system will not influence the results of the experiments. This is the case since the difference is constant during all the experiments that are carried out. For that reason the experiments are comparable with each other. When the results of the experiments are however compared with the situation from the real system, the numbers used in this validation should be taken into account. For these given reasons, the above elaborated simulation model can be considered valid based on its performance.

Furthermore, it is also checked if the transportation times in the model are comparable to reality. This is done using the timer in the simulation model and comparing this with the numbers from Appendix H. When these numbers were compared, they were similar.

Structural Validation

Besides checking if the model gives the right performance, also the behaviour of the model itself needs to be validated. This can be done by adjusting variables in the model to a minimum or maximum and check if the model performs as could be expected.

This can firstly be done by minimizing the available buffer capacity in between the machines. This should minimize the output of the system since the failure on one machine directly stops all the other machines on the production line. When the model is run with no buffer capacities in between the machines, indeed all the other machines of the production line became blocked or starved as well when a failure on one machine occurs.

Secondly, all machines of the production line are made reliable to check if in this case the output of the process is maximised. When this is done indeed the system produced at its maximum, which is the same as the processing capacity of the bottleneck machine.

Finally, it is checked how the model performs if it is not given enough input to continue the process. This is done by only giving the depalletiser one pallet to process. The bottles that are removed from the pallet entered into the process and reached the palletiser. However, the amount of boxes that are entered into the process could only fill one pallet. For this reason after the first pallet is created all the other machines become starved and multiple boxes are left waiting in front of the palletiser.

Furthermore, to check if this model is indeed behaving the same compared to the reality, experts that work on this production line were asked to review the model. They confirmed the previous made arguments as reason for why the model is given a higher output compared to the situation in reality.

5.2 Experiments with the simulation model of line 52

Following from the third chapter some conclusions were drawn with regard to protective capacity, buffer capacity and the reliability of a system. To apply these conclusion to the situation of production line 52, some experiments with the previous elaborated model are conducted. These different experiments are elaborated below. To do so, first the experimental set-up is elaborated. After that the results of the experiments with regard to reliability, protective capacity and finally buffer capacity are elaborated.

5.2.1 Experimental set-up

Before the experiments can be ran, some experimental factors need to be determined. These are the run length, the number of replications and the warm-up period of the simulation run. Each of them is elaborated below.

Run Length

For the experiments a run length of **24 hours** is chosen. This is chosen for the same reasons as were elaborated in the third chapter.

Number of Replications

To make sure the results of the experiments do not rely on coincidence, multiple replications of the experiments need to be carried out. In the third chapter a number of ten replications was chosen. In this chapter however a number of **20 replications** is considered. This is chosen since both the variability in the model is high and the number of experiments that is carried out is less compared to the experiments carried out in the third chapter.

Warm-up Period

At the start of a run, the bottles first need to get from the depalletiser to the palletiser and are in a transient state. This transient state changes after a certain period of time to a steady state. This period of time should be equal to the warm-up period of the model, since for this thesis the focus is on the steady-state behaviour. In this model it takes approximately two hours for the first bottle to arrive at the palletiser, this means that the warm-up period should be set equal to **2 hours**.

5.2.2 Target Values MTBF and MTTR

In chapter four it was found that some machines do not meet the target values that were defined based on the buffer time and recovery time of the buffers in between the machines. To see what the influence is when one of these machines does meet these target values, different experiments are carried out. These results are displayed in Table 5.2 below.

Table 5.2: Results Experiments KPI Performance Target Values MTBF and MTTR

Target Value	Machine	Average Performance
MTBF	Depalletiser	82.7%
	Filling Machines	82.8%
	Case Packers	84.1%
MTTR	CPL´s	82.4%
	Case Closers	82.8%
Current		82.4%

Looking at these results it can be seen that increasing the MTBF of the packaging machines to its target value increases the performance of the system the most. It can be concluded that only increasing the MTBF of the packaging machines significantly increases the performance of the system ($p=0.05$). However, increasing this value will be a hard job since the current mean time between these failures is very low and this time needs to be more than doubled. This means that a deep investigations needs to be carried out on these machines to see which causes are creating the failures or the replacements of these machines might be considered. The causes of the failures can be found using the diagram that was displayed in Appendix M.

Finally, it is checked what the performance of the system would be when all the machines are made equally reliable as the before mentioned targets. To do so an experiment is carried out in which all MTBF and MTTR of the machines are set equal to the targets. The results of this experiment can be found in Table 5.3 below.

Table 5.3: Result experiments all machines target values MTTR and MTBF

Average throughput [bottes/hour]	69439
Average performance [%]	86.8%
Average increase performance compared to current [%]	5.4%

When all machines perform at the target values the performance of the system indeed increases significantly ($p=4.95*10^{-7}$). From this it can be concluded that it is advisable to perform research into why the machines are failing that often or why the stoppages on the machines are taking that long.

The results of the above explained experiments are displayed in Figure 5.4 below. These results are displayed in histograms in which the vertical axis starts at 80%. This has been chosen since in this way the differences between the different experiments can be seen more clearly.

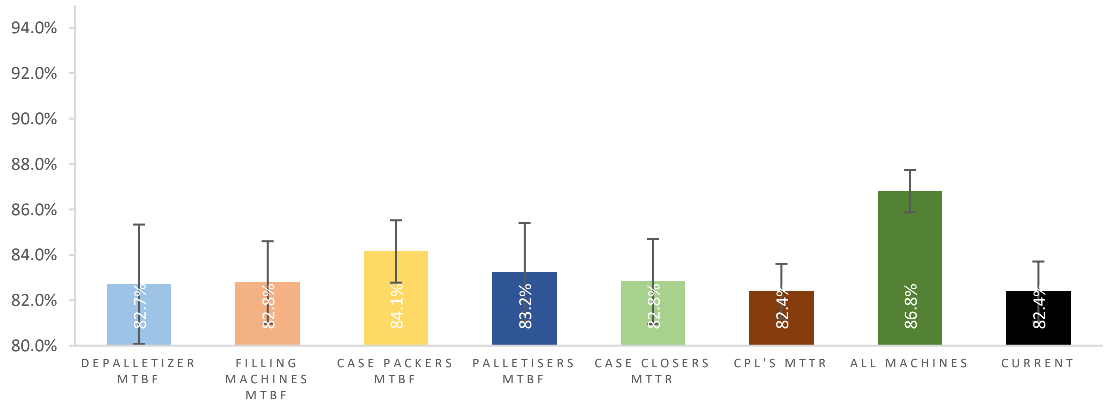

Figure 5.4: Results Performance Experiments Target Values MTBF and MTTR

Following from these experiments a plan should be made for each machine to determine how the machine reliability can be increased. This can be done based on the causes of failures that were found in in chapter four.

5.2.3 Changing the shape of the protective capacity

Following from the results with regard to protective capacity that were given in the third chapter, it would be interesting to see if the shapes there were identified as best performing in the third chapter also performed best in the simulation model of this real situation. To do so, different experiments are carried out that increase the protective capacity with steps of 10% based on the five different shapes. The input variables that are used for these experiments can be found in Appendix I.1. The nominal speeds of the machines are set equal to the capacities that added protective capacity in steps of 10%. For the catch-up speeds that could be assigned to some of the machines a speed of 10% higher than the nominal speed is assigned. The results of these experiments can be seen in Figure 5.5 below.

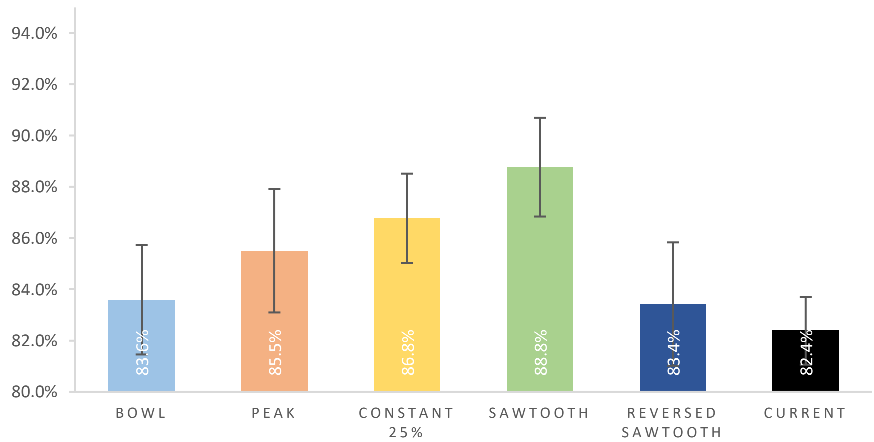

Figure 5.5: Results experiments shapes protective capacity line 52

The peak shape (p=0.019), the constant shape (p=0.0003) and the sawtooth shape ($p=7.93*10^{-6}$) give a significantly higher performance compared to the current situation. The sawtooth shape performs significantly better compared to the peak shape in this situation as well (p=0.028).

However, in these experiments it is tested what the effect would be of setting the nominal speeds according to the shapes. It would however be interesting to see what the results would be if the sawtooth shape is implemented and not the nominal speeds of the machines, but the catch-up speeds of the machines are set equal to the allocation that follows this shape. The input variables that are used for this experiment can be found in Appendix I.2. The results are shown in the table below.

Table 5.4: Results experiments sawtooth shape when catch-up speed is assigned according to the shape

Average throughput [bottes/hour]	68636
Average performance [%]	85.8%
Average increase performance compared to current [%]	4.1%

The system performance indeed increases significantly when the sawtooth shape is adjusted and the catch-up speeds are set to perform according to the sawtooth shape (p=0.0004). However, the performance is significantly less compared to the situation in which the nominal speeds are set equal to the capacities that are determined by the sawtooth shape of protective capacity (p=0.002).

In the production lines of Heineken however the bowl shape, also known as the *"V-graph"*, is adapted on the production lines. In this case the machines that are located closest to the bottleneck machine have the lowest amount of protective capacity. This is opposite to the peak shape in which the highest amount of protective capacity is allocated to the machines closest to the bottleneck machine and the sawtooth shape in which the machine after the bottleneck has the highest amount of protective capacity.

Looking at the technical limitations of the machines which are part of production line 52, implementing the peak, the constant or the sawtooth shape is technically not possible. This is caused by the maximum processing capacity of the CPL's, the filling machines and the packaging machines, and in case of the constant shape also the depalletiser, since they are not able to produce at the speeds that is suggested by the shapes. For this reason implementing these shapes is not possible for this production line, unless new machines are purchased or the current machines are adjusted.

However, when these results were presented to Heineken it was asked what would be the effect of implementing the sawtooth shape within the technical possibilities of the system. They also noted here that the CPL's should be able to produce at a higher capacity per hour. When this capacity for the CPL's is used together with the other available maximum capacities of the machines as is shown in Appendix I.3, the following results as are displayed in Table 5.5 are derived.

Table 5.5: Results experiments sawtooth shape within technical possibilities line 52

Average throughput [bottes/hour]	67557
Average performance [%]	84.4%
Average increase performance compared to current [%]	2.5%

The system indeed performs significantly better when the sawtooth shape is used within the technical possibilities of the system compared to the current performance (p=0.0004).

Furthermore, the question was asked what the effect would be of decreasing the processing capacity of the pasteurizer, the bottleneck machine, to such a level that the sawtooth shape with steps of 10% could be realised. This means that the consideration that is taken into account here is if it is better to have a lower output of the bottleneck machine and having less blockage and starvation on the bottleneck compared to how the system is currently performing. To test what the effect would be of this the pasteurizer is set to process at a capacity that is 40% lower than that of the maximum capacity of the CPL's. What the processing capacities of the different machines will be due to this is displayed in Appendix I.4. The results of the experiments that are carried out with these settings are displayed in the table below.

Table 5.6: Results experiments lower capacity pasteurizer

Average throughput [bottes/hour]	62790
Average performance [%]	78.5%
Average increase performance compared to current [%]	-4.7%

From these results it can be concluded that it is not advisable to decrease the processing capacity of the pasteurizer, since this also decreases the total performance of the system significantly. This means that the effect of having the pasteurizer process at a lower capacity has more influence on the throughput of the system compared to decreasing the amount of starvation and blockage on the pasteurizer.

5.2.4 Adding extra buffer capacity

Finally, it would be interesting to see if the results with regard to adding extra buffer capacity that were found in the third chapter, also hold in a situation in the field of practice. In this situation, the most unreliable machines are the packaging machines and the case closers. For this reason it is tested what the effect is of increasing the buffer capacity by a factor of two, either before these unreliable machines or directly in front or after the bottleneck machine. These results can be seen in Figure 5.6 below.

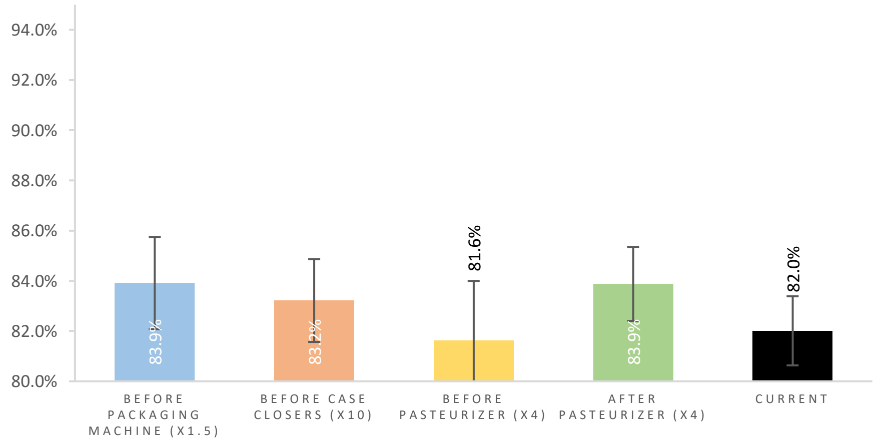

Figure 5.6: Results experiments extra buffer capacity line 52

From these results it can be concluded that adding extra buffer capacity in front of the pasteurizer decreases the performance of the system compared to the current situation. However, increasing the buffer capacity in front of the packaging machines and after the pasteurizer does increase the performance of the system. This is however dependent on the fact to which degree the capacity is increased. Since in case the capacity in front of the packaging machines is increased with a factor of four, the performance of the system even decreases. This can be explained by the fact that in that case the bottles need to travel a too long distance, which has an impact on the performance of the system.

When a significance level of 0.05 is used no significant difference exists between the different alternatives. However, it can be stated with a 90% confidence that adding a buffer in front of the packaging machines (p=0.090) and after the pasteurizer (p=0.06) significantly increases the performance of the system. The lower confidence of the results is due to the fact that a lot of variability exists in the system.

These results are in line with the results that have been found in the third chapter of this thesis in which it was stated when the most unreliable machine was located downstream of the bottleneck it is best to place a larger buffer either after the bottleneck machine or in front of the most unreliable machine, which in this case is the packaging machine.

5.3 Conclusion

In this chapter a simulation model that represents production line 52 of the Heineken brewery located in Zoeterwoude is created. With the use of this model the results that were found in the third chapter are applied to a situation from the field of practice. It is researched how the performance of this production line can be increased using the found improvement alternatives. From these experiments a few conclusions can be drawn.

First of all, with regard to increasing the reliability of the machines, it is found that when all machines that are part of production line 52 are set to meet the target values of the mean time to repair and the mean time between failures, the performance of the system significantly increases. Furthermore, when only the reliability of the packaging machines is increased, the performance of the whole system increases as a consequence.

Secondly, with regard to the different shapes of allocating protective capacity it can be stated that a preference exists for the constant, sawtooth and peak shape against the reversed sawtooth and bowl shape. In the case of Heineken, it is found that these three shapes significantly outperform the other two shapes, which is comparable with the results found in the third chapter. However, implementing these shapes of protective capacity with steps of 10% is technically not possible on production line 52. For that reason it is checked if the performance of the system could be increased by implementing the sawtooth shape within the technical possibilities of the system. This has proven to be possible and can create an improvement of performance compared to the current situation. Besides, it is checked what the influence would be on decreasing the processing capacity of the pasteurizer, based on being able to implement the sawtooth shapes with steps of 10% protective capacity. This has proven to significantly decrease the performance of the system and it is therefore not advisable to be implemented at production line 52 of Heineken.

Finally, it is checked what the effect is of adding extra buffer capacity along the production line. From these experiments it followed that either adding buffer capacity after the pasteurizer or before the bottleneck machine significantly increases the performance with a confidence level of 90%. This is in line with the results that were found in the third chapter in which it was stated that whenever the most unreliable machine is located downstream of the bottleneck, the larger buffer should be located either after the bottleneck machine or in front of the most unreliable machine. From this it can be concluded that it indeed also holds in a situation in the field of practice.

5.4 Recommendations for Heineken and production line 52

Following from the above carried out experiments and the above given conclusions, some recommendations with regard to implementation of the results can be given to Heineken and production line 52.

The first recommendation regarding implementation which can be given is related to the target values that are derived from the buffer time and the recovery time of the buffers in relationship with the mean time to repair and the mean time between failures. It is advisable that the current mean time between failures and mean time to repair are constantly checked against these target values. To do so, an excel file is made in which this can be done for production line 52 of Heineken. However this excel file is currently only created for production line 52, it could be extended to be used by all production lines of Heineken and production lines of other manufacturing companies as well.

This file shows for each machine how the current MTBF and MTTR are performing in relationship with the minimum and maximum targets that were derived in the previous chapter. The current MTBF and MTTR are shown for the past week, the past month and the current year and are updated automatically when new input is available. This means that it can be continuously checked how the current values are performing compared to the targets. To do so, a green, orange or red dot is displayed that shows which machines are critical with regard to both these times. The excel file is displayed in Appendix L.

Based on these values it can be determined which machines need extra attention with regard to maintenance to improve the current values of the MTBF and MTTR. This can be done based on the causes that are displayed in Appendix M. As was concluded in this chapter, especially increasing the MTBF of the packaging machines significantly increases the performance of the system. It is however advisable to try and meet the target of all these values, since that increases the performance of the system even more. Increasing the reliability of the machines mainly costs extra man hours of maintenance personal and operators. The estimation is that the extra maintenance costs are below the extra profit it will create and therefore it is profitable to try and increase the reliability of all the machines up to these target numbers.

With regard to the implementation of the found results it can be stated that it is hard to implement any of the significant better performing shapes within the technical boundaries of the system. This is due to the fact that the especially the CPL's, the filling machines and the packaging machines are limited by their maximum processing capacity. However, when it is investigated what is possible within the boundaries of the system it can be stated that implementing the sawtooth shape, with limitations of the capacities of the machines, does increase the performance of the system. For this reason it is advised to Heineken to change these capacities in real life and track the output of the system. It should however be noted that losses that are caused by wear and tear should also be considered. When this is implemented, this means that the total output of the system can be increased with 2.5%. The costs of implementing this shape are mainly personal costs for employees who are able to change the setting of the machines. This will be a lot lower compared to the extra profit which can be made and it is therefore advisable to implement the sawtooth shape at production line 52.

Furthermore, with regard to future production lines at Heineken or future investments in new machines, it can be advised to rethink the strategy and scientific reasons for the use of the *"V-shape"* as the way to allocate a production line. This means that looking at future scenarios in which a new production line will be build, it would be advisable to see if either the peak, constant or sawtooth shape is able to be implemented. This means that machines need to be purchased that are able to produce at these processing capacities. As this research has shown, the *"V-shape"*, also known as the bowl shape, is performing less compared to the peak, constant or sawtooth shape. However, this "*V-shape"* is very embedded in the strategy to improve production line performance by Heineken and doing this differently will ask for a change in culture, which will be a difficult process. The same was concluded in the thesis of Emily Verwaal (2018), who stated that an increasing amount of protective capacity towards the bottleneck machine, as is used in the peak and sawtooth shape, outperforms a decreasing amount of protective capacity towards the bottleneck. Although this advice has been given in the past, the "V-*graph"* is still the main philosophy at Heineken for the design of production lines. For the above mentioned reasons it can be said that when a new production line will be build, it would be wise to rethink the design of the production line and allocate the production line according to the peak, sawtooth or constant shape.

With regard to the buffer capacity that is present at production line 52 it can be said that the amount of buffer capacity that is currently present in between the machines is probably sufficient enough and adding extra buffer capacity does not necessarily increase the performance of the system. With regard to future production lines of Heineken it can be advised to investigate which machines that are part of the system are the most unreliable and allocate the amount of buffer capacity in the production line based on these properties of the machines.

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6 Conclusion and Recommendations

Firstly, the conclusion of the research is given in this chapter. In the conclusion the sub-questions that were asked at the beginning are answered. Afterwards, the results and how these were derived in this thesis are discussed. Finally, recommendations for both Heineken, production line 52 and future scientific research are given based on this discussion.

6.1 Conclusion

This paragraph gives the conclusion of the conducted research that answers the main research question:

"What are the root causes for a loss of productivity in one-way bottling and packaging production lines and how can this loss be decreased?"

To do so, five sub-questions were drawn up that needed to be answered to be able to answer the main research question. The following paragraphs discuss each sub-question.

"Which factors influence the productivity of a production line?"

Following from the available literature and information from the field of practice, different factors could be identified that influence the productivity of production lines.

This is first of all dependent on the technical properties of production lines. These properties of the machines and production line can be defined as paced or un-paced, synchronous or asynchronous and reliable or unreliable. Besides, also the technical properties of the buffers play a role. Furthermore, the maintenance of the production line determines the performance of the system as well. The performance of the system is dependent on when and how the maintenance is carried out, this can be reactive, preventive, proactive or aggressive. Aggressive maintenance is nowadays mostly being used by manufacturing companies since this not only strives at maintaining the current performance, but also at continuous improvement.

The before mentioned factors are all connected to the reliability of the machines. The reliability of the machines can be defined by both by the *mean time to repair* and the *mean time between failures*. The first defines the average time a failures takes. This can be either including or excluding the reaction time on a failure. The second measure defines the average time between two adjacent failures. The higher this time, the less stoppages occur on a machine or production line. The loss of performance of a production line can be categorised into six *"major losses"*, being set-up losses and adjustment losses, minor stops and idling losses, speed losses, breakdown losses, reject and rework losses and reduced yield losses. Of these losses the loss caused by minor stoppages and idling usually influences the productivity the most.

The influence these failures have on the production line is dependent on several factors. These are mainly the processing speeds of the machines and the buffer capacity of the conveyor belt that is located in between these machines. During a failure these factors determine the buffer time, which is the time the buffer can absorb the failure before it affects other machines. For a production line it is desirable that the mean time to repair is shorter than the available buffer time, since in that way there is less influence of a stoppage on different machines. These factors furthermore determine the recovery time of the buffers. This is the time after a failure that it takes for the buffer to be depleted or replenished to the nominal fill level again. It is desirable for the mean time between failures to be below this time, since in that way the buffer is more likely to be at the nominal fill level again before the next failure occurs. In this way a stoppage has less influence on the machines surrounding it.

"Which of these factors can be altered to improve the overall productivity of a production line?"

Different approaches exist with regard to either balancing or un-balancing a production line. When a production line is un-balanced, this means that the mean processing times of the machines are differentiated. The first approach with regard to this is the Theory of Constraints and the corresponding Drum Buffer Rope methodology. This approach suggests that the improvement of a production line should be focussed on the constraint machine and it should be made sure that this machine is able to produce at all time. This approach suggests that the largest buffer should be placed in front of this machine. The Kanban system however suggests a Just in Time delivery, suggesting smaller and equal buffer capacities in between the machines. Another approach with regard to the allocation of production lines is the bowl phenomenon. This methodology states that the machines with the highest processing times and variabilities should be placed at the beginning and end of production lines. Other approaches in the literature however disagree and state that the highest variabilities and processing times should only be placed only at the end of a production line. Furthermore, different approaches exist regarding the allocation of protective capacity, the extra amount of processing capacity that is allocated to the non-constraint machines. This could be done in different shapes and with different amounts of protective capacity. This area is however not investigated intensely in the available literature.

"What advice can be given to improve the overall productivity of a one-way bottling and packaging production line?"

To investigate the effects of the theories and approaches that were discussed in the previous question, a generic model of a one-way bottling and packaging process was created. Different improvement alternatives were applied on this model. First of all, the improvement alternatives based on the five different shapes of protective capacity were tested, these are the bowl shape, the peak shape, the constant shape, the sawtooth shape and the reversed sawtooth shape. All five shapes were tested in different configurations with regard to reliability. All the shapes have proven to give a significantly higher performance compared to having no protective capacity in place. From these experiments it can be concluded that in most cases the peak, constant and sawtooth shape perform better compared to the reversed sawtooth and bowl shape. Furthermore, the preference for a certain shape changes when one machine of the production line is assumed less reliable compared to the other machines.

Besides, increasing and decreasing the amount of protective capacity respectively significantly decreased or increased the performance of the system. However, the increase of performance is less when the amount of protective capacity is increased from 10% to 15%, compared to the increase from 5% to 10%. This difference decrease even further when more protective capacity is allocated to the machines. Assigning all the machines an amount of protective capacity in steps of 15% is also not always possible due to technical limitations of the machines and quality losses.

The next experiments that were carried out are related to the amount of buffer capacity. From these experiments it could be concluded that the more buffer capacity is added in between the machines, the significantly higher the performance of the system became. However having a lot of buffer capacity in place is not always possible technically or financially and is beneficial only to a certain limit. For that reason, it was investigated at which place in the production line an extra amount of buffer capacity can best be assigned. If all machines have equal reliabilities it is best to place the extra amount of buffer capacity directly after the bottleneck machine. However, when the most unreliable machine is located upstream of the bottleneck it is best to place the extra amount of buffer capacity directly in front of the bottleneck. When the most unreliable machine is located downstream of the bottleneck it is best to place the extra amount of buffer capacity directly after the bottleneck or in front of the most unreliable machine. With regard to when the amount of protective capacity needs to be activated, no preference exists when medium sized buffers are placed in between the machines. However, when larger buffers are added in between the machines it gives a significantly higher performance when the amount of protective capacity is activated early on if the buffers are starting to become emptier or fuller compared to their nominal fill level.

"How do the above described factors act in the field of practice as can be seen at production line 52 of Heineken?"

Following from the above conducted analysis it became clear which factors influence the productivity of a one-way bottling and packaging production line. The next step was to investigate how the factors that were defined in question one and two act in a situation in the field of practice. To do so, a case study was performed at production line 52 of the brewery of Heineken which is located in Zoeterwoude.

The first step in this case study was to investigate what the current performance of production line 52 is. This was done with the use of a data analysis in which the data with regard to reliability of the machines was collected over the period of January 2019 – August 2019. Furthermore, the data with regard to buffer capacity, buffer control and the processing speeds of the machines was collected.

Besides, it was calculated for every machine what the buffer time and recovery time are. These values were respectively compared with the mean time to repair and the mean time between failures of the machines. From these values, together with the before found results it could be concluded which machines of this production line are the most critical. These are first of all the machines around the bottleneck machine, the filling machines and CPL's. Furthermore, the area in which the bottles are packaged in boxes is critical as well.

"What advice can be given to Heineken with regard to improving the productivity of production line 52?"

Once the current performance of production line 52 was determined, the next step was to investigate ways in which this performance can be improved. This was done by applying the results of the third question to the situation of production line 52 with the use of a simulation model. This simulation model was created using the model from the third question. This model was however extended and more details regarding production line 52 were added. Following from the conducted experiments, some advices can be given to Heineken and production line 52.

First of all, with regard to the reliability of the machines it can be stated that the performance of the system significantly increases if the mean time to repair and mean time between failures is equal to respectively the buffer time and the recovery time of the buffers. This means the time it takes for a failure on one machine to influence another machine and the time it takes for the buffer to be restored to the nominal fill level respectively. Especially increasing the mean time between failures of the packaging machines increases the performance of production line 52. Following from this, it is advised to continuously check if the targets for the mean time between failures and the mean time to repair are met. To do so, an excel file was created in which this can be done for every week, month and year. Following from this, a plan should be made to increase the reliability of the machines that are not meeting the target values.

Furthermore, with regard to the shapes in which the protective capacity should be allocated along the production line, the experiments have shown that the sawtooth, constant and peak shape significantly perform better than the current performance, the bowl shape and the reversed sawtooth shape. Out of these three shapes the sawtooth shape gives the significant highest performance. Due to this, it is advised for Heineken to implement the sawtooth shape at production line 52. This can at first be done within the technical possibilities of the system, using the current maximum processing capacities of the machines. In the future however, it should be tried to increase the capacities of the CPL's, filling machines and packaging machines to completely be able to adapt the sawtooth shape in the production line. Looking at future scenarios in which new production lines will be build, it is advised to check which shape of protective capacity gives the highest performance based on the properties of the new production line. Following from that it is advised to invest in machines that are able to produce at capacities that apply to this shape. This means that the strategy behind the *"V-shape"*, which is adapted at all production lines of Heineken needs to be rethought together with the reasons why this shape is chosen to be adapted.

Besides, with regard to the buffer capacity it was found that the performance of production line 52 increases whenever extra buffer capacity is added either directly after the bottleneck machine, the pasteurizer or in front of the packaging machines, which are one of the most unreliable machines of the production line.

Finally, the answering of the above mentioned sub-questions results in an answer that can be derived for the following main research question:

"What are the root causes for a loss of productivity in one-way bottling and packaging production lines and how can this loss be decreased?"

In this thesis multiple root causes for a loss of productivity have been researched together with ways in which the productivity of a production line can be increased. This is first of all the allocation of protective capacity. In this thesis it is shown that the performance of a system increases whenever protective capacity is allocated to the non-bottleneck machines. Regarding the way in which the shape of protective capacity should be allocated, it can be stated that in order to increase the productivity it is best to either implement the sawtooth, constant or peak shape at a production line. Furthermore, it should be taken into account that increasing the capacities of the machines will also cause wear and tear, which in their turn can cause more failures of the machines. This relationship is important to keep in mind when implementing a certain shape of protective capacity at a production line.

Secondly, it can be stated that the performance of the system increases due to adding extra buffer capacity in between machines. It is dependent on the reliability of the machines at which place in the production line an extra amount of protective capacity can best be allocated. Besides, it should be noted that there is a limit to which the amount of buffer capacity should be increased, since too much buffer capacity could decrease the performance of the system.

6.1 Discussion

In this paragraph the results and the way in which the results are derived in this thesis are discussed. It is first of all checked if the method that has been used, answers the main research question. Looking at this research question, it can be said that this is a relatively broad question and it could have been answered in multiple ways. In this thesis it is chosen to investigate the reliability, buffer capacity and protective capacity as variables to increase the productivity of the system. It could however also been investigated in which ways the reliability for example could have been increased with a proper maintenance strategy. This is however left out of the scope in this research.

Furthermore, a lot of assumptions have been made in this thesis to be able to model a production line. In the field of practice however multiple different variables also play a role besides the variables that are taken into consideration in this thesis. This is first of all the fact that only short stoppages have been taken into account in this research. This has been chosen since only the effect of these stoppages can be influenced by the variables that are taken into consideration. However, also longer stoppages cause a loss of performance of the system and are determent for the productivity of the system. This means that it is also important to determine ways in which the longer stoppages can be limited, which is left out of the scope of this thesis.

Besides, in this thesis it is chosen to use Simio as a simulation software to conduct the experiments. This means that the results that can be derived are limited due to that. When another software was used to do the simulations, different results could have been found. It is however not known if this would be the case.

Furthermore, due to unknown relationships some factors are not taken into account. This can be seen in the relationship between machines running at a higher capacity and wear and tear on the machines. It is not known how much reliability is lost due to these higher speeds and this is therefore not taken into account in the model. However, it can be said that there is a relationship between these factors, but it is hard to determine how big this relationship is. This is caused by the fact that this is dependent on the maintenance that is carried out on the machines, how old the machines are and for what capacities the machines are designed. This means that this relationship is different for every production line and every individual machine.

Besides, in this thesis the location of the bottleneck machines is assumed to be relatively in the middle of the production line. This limits the results of these experiments to production lines where the bottleneck is located at approximately the same place. This means that for production lines where the bottleneck is located at the beginning or the end of the line, different results could have been derived.

6.2 Recommendations

Finally, in this paragraph some recommendations are given. First of all recommendations for future scientific research are given followed by recommendations for the field of practice, Heineken and production line 52.

6.2.1 Recommendations for future scientific research

First of all, it can be stated that in this research the results of the generic model are only applied to one production line: production line 52 of Heineken Zoeterwoude. It would however be interesting to investigate if these results also hold in the case of a different production line of Heineken or of different companies.

Furthermore, in this research only a few configurations with regard to reliability, protective capacity and buffer capacity are taken into consideration. However, the question could be asked how the different shapes of protective capacity would perform in more reliable production lines or production lines with two very unreliable machines. Besides, only five shapes of protective capacity are taken into consideration. For future research it would be interesting to see if different shapes exist that could be applied. This could for example be shapes that do not increase with the same steps or shapes that are non-linear. A combination between shapes could also be tested: what would for example be the effect of having a constant shape before the bottleneck machine and a peak shape after the bottleneck machine? With regard to the steps in which extra protective capacity is allocated to the machines, more configurations could be tested as well. What would for example be the effect of increasing the steps of protective capacity based on the reliability of the machines? Or in an decreasing amount of percentage? Following from this an even higher performance could be found based on different configurations.

Besides, it would be interesting to see what the effect would be of having the bottleneck machine located at a different position on the production line. As was stated in the previous paragraph of this chapter, in this thesis only one location of the bottleneck machine is assumed. For this reason investigating the effect on the productivity in combination with buffer capacity, reliability and protective capacity when the bottleneck machine would be located somewhere else on a production line would be interesting.

Furthermore, investigating the relationship between quality losses and having the machines operate at high processing speeds should give insights in the effects in the field of practice of the protective capacity. However, this would be very hard to do since this relationship id dependent on a lot of factors.

Besides that, future research could investigate which factors besides buffer capacity, protective capacity and reliability play a role in the problem of production line productivity. This could for example be a research into which maintenance strategies would be the most appropriate to use in which situation to increase the productivity of the system.

Finally, in this thesis it is assumed that protective capacity is activated based on the fill level of the buffer either before or after the machine. It would however be very interesting to see if a dynamic system can be set in place that controls the processing capacities of the machines based on failures of machines further down the production line. This means that when a machine at the end of the line is experiencing a failure, machines at the beginning of the line should already react on this. Future research could investigate what the effect would be of this and in what way such a system could best be installed on a production line.

6.2.2 Recommendations for the field of practice

The recommendations that can be given for the field of practice can be divided in the levels of focus that were given in Figure 1.3. First of all general recommendations for the field of practice in which one-way bottling and packaging production lines are used, are given. Secondly, some recommendations for the improvement of the productivity of production lines are given for Heineken. Finally, some recommendations regarding the productivity of production line 52 are discussed.

Field of practice

For the field of practice it is recommended to investigate all the properties of the system in detail before installing a production line. This means that the most unreliable machines need to be identified and buffer capacity in between the machines needs to be allocated based on that. Furthermore, before installing a production line it would be wise to investigate which machine will become the bottleneck of this production line. Based on that and the reliability of the different machines, it can be determined which shape of protective capacity would perform best in the case of that particular production line. This means that before installing a production line, it is advised to determine beforehand what the reliabilities of the machines will be and which machine will be the bottleneck machine.

Once this has been determined it is advised to use the method that has been used in this thesis in order to find the appropriate allocation of protective capacity and buffer capacity.

Furthermore, it is recommended for the field of practice to keep track of the mean time between failures and mean time to repair in relationship with respectively the recovery time and the buffer time. To do so, it is recommended to create an excel file similar to the one proposed in the fifth chapter. When machines are not meeting these target values it is recommended to take action with regard to maintenance on these machines. Which causes of failures need to be reduced or mitigated can be seen if a diagram as was discussed in chapter five is created. For that reason it is recommended for manufacturing companies to create such a diagram for their production lines.

Heineken

First of all, it is important for Heineken that all the data that is necessary to determine the performance of the system and the variables that play a role, is available. As was seen in the data analysis of the case study in the fourth chapter, a lot of data needed to be collected with the use of manual measurements. This is very time consuming and when this data is collected properly it would be easier to analyse the performance of the system. Due to this it can be advised to Heineken to properly document all the variables that determine the performance of the system. These are both the properties of the conveyor belts and the properties of the machines. A lot of this data is available, but it is not always clear what the data means or in what way it is collected. If this is documented in a more organised way it would be easier in the future to determine the factors that are playing a role in determining the performance of a production line.

Secondly, it can be recommended to Heineken to rethink the strategy behind the use of the *"V-shape"* as idea behind the allocation of the protective capacity of all its production lines. Although this shape is seen by Heineken Global as the ultimate strategy to improve performance, this is not always the case as was proven in the previous chapters. This is due to the fact that every production line has its own characteristics and for that reason different shapes of protective capacity work best in different production lines. Using the conclusions that are given in this thesis the proper allocation of protective capacity can be found.

Production line 52

For production line 52 recommendations can be done with regard to implementing the results that were found in this thesis. For production line 52 it can be advised to implement the sawtooth shape in the production line even though it is limited due to the technical capabilities of the machines. However, when this is implemented at the production line, the wear and tear that is caused by running at these high processing capacities should be considered. To do so, when the new shape is implemented it should be tracked if the reliability of the machines decreases after the implementation. When this is the case it should be considered if this is worth the extra throughput that it creates.

This can be done with the implementation excel that was proposed in the fifth chapter. With the use of this excel Heineken can keep track of the *Mean Time Between Failures* and the *Mean Time To Repair* of the machines that are part of production line 52. Whenever these values do not meet the target values that are set based on the buffer time and recovery time, action needs to be determined to increase the reliability of the machines. This can be done based on a diagram in which for every machine the main causes of failures are displayed. Based on these causes proper maintenance actions should be determined.

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7 References

Almeanazel, O. T. (2010). Total Productive Maintenance Review and Overall Equipment Effectiveness Measurement. *Jordan Journal of Mechanical and Industrial Engineering, 4*(4), 517-522.

Alsyouf, I. (2007). The role of maintenance in improving comanies' productivity and profitability. *International Journal of Production Economics, 105*(1), 70-78.

Aman, Z., Ezzine, L., Fattah, J., Lachhab, A., & Moussami, H. E. (2017). Improving efficiency of a production line by using Overall Equipment Effectiveness: A case study. *Proceedings of the International Conference on Industrial Engineering and Operations Management*, (pp. 1048-1057). Rabar, Morocco.

Atwater, J. B., & Chakravorty, S. S. (1994). Does protective capacity assist managers in competing along time-based dimensions. *Production and Inventory Management Journal, 35*(3), 53.

Barabady, J., & Kumar, U. (2007). Availability allocation through importance measures. *International Journal of Quality & Reliability Management, 24*(6), 643-657.

Bartkowiak, T., & Pawlewski, P. (2016). Reducing negative impact of machine failures on performance of filling and packaging production line - a simulative study. *2016 Winter Simulation Conference (WSC)* (pp. 2912-2923). IEEE.

Basan, N., Coccola, M., & Mendez, C. (2014). An innovative discrete event simulation tool to improve the efficiency of a complex beer packaging line.

Battini, D., Persona, A., & Regattieri, A. (2009). Buffer size design linked to reliability performance: A simulative study. *Computers & Industrial Engineering, 56*(4), 1633-1641.

Benjamin, S. J., Murugaiah, U., & Marathamuthu, M. S. (2013). The use of SMED to eliminate small stops in a manufacturing firm. *Journal of Manufacturing Technology Management, 24*(5), 792-807.

Bernhand, F. (2000). *Bottling and canning lines for the beverage industry: concepts, technology and trends.* Verlag Moderne Industrie.

Birolini, A. (2017). *Reliability Engineering* (8 ed.). Firenze: Springer.

Blackstone, J. H. (2004). On the shape of protective capacity in a simple line. *International journal of production research, 42*(3), 629-637.

Blackstone, J. H., & Cox III, J. F. (2002). Designing unbalanced lines - understanding protective capacity and protective inventory. *Production Planning and Control, 13*(4), 416-423.

British Standard. (1984). *British Standard Glossary of Maintenance Management Terms in Terotechnology.* London: British Standard Institution.

Buzacott, J. A., & Shanthikumar, J. G. (1993). Production lines. In *Stochastic Models of Manufacturing Systems* (pp. 1-12). Prentice Hall.

Cambridge Dictionary. (n.d.). *Production line*. Retrieved from Dictionary Cambridge: https://dictionary.cambridge.org/dictionary/english/production-line

Chan, F. T., Lau, H. C., Ip, R. W., Chan, H. K., & Kong, S. (2005). Implementation of total productive maintenance: A case study. *International Journal of Production Economics, 95*(1), 71-94.

Chitkara, K. K. (2014). *Construction Project Management: Planning, Scheduling and Controlling* (3 ed.). New Delhi: McGraw Hill Education.

Choong, Y. F., & Gershwin, S. B. (1987). A decomposition method for the approximate evaluation of capacitated transfer lines with unreliable machines and random processing times. *IIE Transactions, 19*(2), 150-159.

Craighead, C. W., Patterson, J. W., & Fredendall, L. D. (2001). Protective capacity positioning: impact on manufacturing cell performance. *European Journal of Operational Research, 134*, 425-438.

Davis, L. E. (1966). Pacing effects on manned assembly lines. *International Journal of Production Research, 4*(3), 171.

de Smet, R., Gelders, L., & Pintelon, L. (1997). Case studies on disturbance registration for continuous improvement. *Journal of Quality in Maintenance Engineering, 3*(2), 91-108.

Donoghue, C., Jackson, G., Koop, J. H., & Heuven, A. J. (2012, May). *The Environmental Performance of the European Brewing Sector*.

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *The Academy of Management Review, 14*(4), 532-550.

Flynn, B. B., Sakakibara, S., Schroeder, R. G., Bates, K. A., & Flynn, E. J. (1990). Emprical research methods in operations management. *Journal of Operations Management, 9*(2), 250-284.

Gay, C. (2016, January 25). *8 Wastes of Lean Manufacturing*. Retrieved from MachineMetrics: https://www.machinemetrics.com/blog/8-wastes-of-lean-manufacturing

Goldratt, E. (1988). Computerized shop floor scheduling. *International Journal of Production Research, 26*(3), 443-455.

Goldratt, E. M. (1984). *The Goal*. North River Press Publishing Corporation.

Goldratt, E. M. (1997). *Critical Chain*. Taylor & Francis Ltd.

Halpin, D. W., & Senior, B. A. (2010). *Construction Management* (4 ed.). United States of America: John Wiley & Sons, Inc.

Hancock, D. R., & Algozzine, B. (2006). *Doing Case Study Research*. New York and London: Teachers College Press.

Härte, F. H. (1997). *Efficiency Analysis of Packaging Lines*. Delft: Delft University Press.

Hassanain, M. A., Froese, T. M., & Vanier, D. J. (2003). Framework for asset maintenance management. *Journal of Performance of Constructed Facilities, 17*(1), 51-64.

Heineken. (2019). *Opbouw en werking CPL colonne 52*.

Heineken. (2019). *Opbouw en werking inpakmachine colonne 5*. Zoeterwoude.

Heineken. (2019). *Opbouw en werking ontfoliemachine colonne 5*. Zoeterwoude.

Heineken. (2019). *Opbouw en werking pasteur col 52*. Zoeterwoude.

Heineken Nederland. (2018). *MTBA Manual*. Zoeterwoude.

Hendricks, K. B. (1992). Exponential Machines with Finite Buffers. *Operations Research, 40*(6), 1139-1147.

Hillier, F. S., & Boiling, R. W. (1966). The effect of some design factors on the efficiency of production lines with variable operations. *Journal of Industrial Engineering, 25*(8), 651-658.

Hudson, S., Shaaban, S., & McNamara, T. (2015). The performance of unpaced production lines with unbalanced mean operation times and unreliability patterns. *Journal of Manufacturing Systems, 37*(1), 164-172.

Imaoka, Z. (2012). *Understand Supply Chain Management through 100 words*. Tokyo: Kougyouchousakai.

Kadipasaoglu, S. N., Xiang, W., Hurley, S. F., & Khumawala, B. M. (2000). A study on the effect of the extent and location of protective capacity in flow systems. *International Journal of Production Economics, 63*(3), 217-228.

Katukoori, V. K. (1995). *Standardizing availability definition*. New Orleans: University of New Orleans.

Kelly, A. (1997). *Maintenace Strategy*. Elsevier.

Kiran, M., Mathew, C., & Kuriakose, J. (2013). Root Cause Analysis for Reducing Breakdowns in a Manufacturing Industry. *International Journal of Emerging Technology and Advanced Engineering, 3*(1), 211-216.

Kourtis, L. K., & Arvanitoyannis, I. S. (2001). Implementation of hazard analysis critical control point (HACCP) system to the alchoholic beverages industry. *Food Reviews International, 17*(1), 1-44.

Lehto, M. R., Landry, S. J., & Buck, J. (2007). *Introduction to Human Factors and Ergnomics for Engineers*. New York, London: Taylor & Francis Group.

Li, J., & Meerkov, S. M. (2000). Bottlenecks with Respect to Due-Time Performance in Pull Serial Production Lines. *Mathematical Problems in Engineering, 5*, 479-498.

Li, J., & Meerkov, S. M. (2008). *Production Systems Engineering*. New York: Springer Science+Business Media.

Li, J., Blumenfield, D. E., Huang, N., & Alden, J. M. (2009). Throughput analysis of production systems: recent advances and future topics. *International Journal of Production Research, 47*(14), 3823-3851.

Liu, Y., Li, J., & Chiang, S.-Y. (2012). Re-entrant lines with unreliable asynchronous machines and finite buffers: performance approximation and bottleneck identification. *International Journal of Production Research, 50*(4), 977-990.

Ljungberg, Õ. (1998). Measurement of overall equipment effectiveness as a basis for TPM activities. *International Journal of Operations & Production Management, 18*(5), 495-507.

Louis, L. (2003). *Protective capacity and time buffer design in theory of constraints controlled discrete flow production systems*. Stellenbosch: Stellenbosch University.

McNamara, T., Shaaban, S., & Hudson, S. (2012). Simulation of unbalanced buffer allocation in unreliable unpaced production lines. *International Journal of Production Research, 51*(6), 1922-1936.

McNamara, T., Shaaban, S., & Hudson, S. (2016). Fifty years of the bowl phenomenon. *Journal of Manufacturing Systems, 41*, 1-7.

McNamara, T., Shabaan, S., & Hudson, S. (2014). Mean time imbalance effects on unreliable unpaced serial flow line. *Journal of Manufacturing Systems, 33*(3), 357-365.

Mourtzis, D. (2016). Challanges and future perspectives for the life cycle of manufacturing networks in the mass customisation era. *Robust Manufacturing Control: Robustness and Resilience in Global Manufacturing Networks*.

Nakajima, S. (1988). *Introduction to TPM*. Portland: Productivity Press.

Padhi, S. S., Wagner, S. M., Niranjan, T. T., & Aggarwal, V. (2013). A simulation-based methodology to analyse production line disruptions. *International Journal of Production Research, 51*(6), 1885-1897.

Patti, A. L., & Watson, K. J. (2010). Downtime variability: the impact of duration-frequency on the performance of serial production systems. *International Journal of Production Research, 48*(19), 5831-5841.

Patti, A. L., Watson, K., & Blackstone Jr, J. H. (2008). The shape of protective capacity in unbalanced production systems with unplanned machine downtime. *Production Planning & Control, 19*(5), 486-494.

Pegels, C. C., & Watrous, C. (2005). Application of the theory of constraints to a bottleneck operation in a manufacturing plant. *Journal of Manufacturing Technology Management, 16*(3), 302-311.

Pike, R., & Martin, G. E. (1994). The bowl phenomenon in unpaced lines. *The international journal of production research, 32*(3), 483-499.

Pintelon, L. M., & Muchiri, P. N. (2008). Performance measurement using overall equipment effectiveness (OEE): Literature review and practical application discussion. *International Journal of Production Research, 43*(13), 3517-3535.

Pomorski, T. R. (2004). Total Productive Maintenance (TPM) Concepts and Literature Review.

Priest, F. G., & Stewart, G. G. (2006). Packaging Technology. In *Handbook of Brewing* (2 ed., pp. 563-607). Taylor & Francis Group.

Rahman, N. A., Sharif, S. M., & Esa, M. M. (2013). Lean Manufacturing Case Study with Kanban System Implementation. *International Conference on Economics and Business Research 2013*, (pp. 174-180).

Rahman, S. (1998). Theory of constraint - A review of the philosophy and its applications. *International Journal of Operations & Production Management, 18*(4), 336-355.

Rajput, H. S., & Jayaswal, P. (2012). A Total Productive Maintenance (TPM) Approach to Improve Overall Equipment Efficiency. *International Journal of Modern Engineering Research, 2*(6), 4383-7386.

Scholten, P. (2016). *Efficiency analysis and improvement at Grolsch*. Enschede: University of Twente.

Sengutpa, S., Das, K., & van Til, R. P. (2008). A new method for bottleneck detection. *Proceedings of the 2008 Winter Simulation Conference*, (pp. 1741-1745).

Sharma, A. K., Shudhanshu, & Bhardwaj, A. (2012). Manufacturing performance and evolution of TPM. *International Journal of Engineering Science and Technology, 4*(3), 854-866.

Shirose, K. (1996). *TPM - Total Productive Maintenance: New implementation program in fabrication and assembly industries*. Tokyo: JIPM.

Simio. (2019, 5 13). *Discrete Event Simulation software use in Industry 4.0*. Retrieved from Simio: https://www.simio.com/applications/industry-40/Discrete-Event-Simulation-software-use-in-Industry-40.php

So, K. C. (1989). On the efficiency of unbalancing production lines. *International Journal of Production Research*, 717-729.

Sorgatz, A., & Voigt, T. (2013). Continuous Control for Buffering Conveyors in Beverage Bottling Plants. *Packaging Technology & Science, 26*, 461-468.

Suehiro, K. (1987). *Eliminating minor stoppages on automated lines*. Portland: Productivity Press.

Suito, K. (1998). Total Productivity Management. *Work Study, 47*(4), 117-127.

Swanson, L. (2001). Linking maintenance strategies to performance. *International journal of production economics, 70*(3), 237-244.

Takahashni, K., Morikawa, K., & Chen, Y.-C. (2007). Comparing kanban control with the theory of constraints using Markov chains. *International Journal of Production Research, 45*(16), 3599-3617.

Torell, W., & Avelar, V. (2004). *Mean Time Between Failures: Explanation and Standards*. Retrieved from American Power Conversion: https://pdfs.semanticscholar.org/de97/955063b165d594e0aa0b55e6e550b51aa51a.pdf

Tsarouhas, P. H. (2015). Performance evaluation of the croissant production line with reparable machines. *Journal of Industrial Engineering International, 11*(1), 101-110.

Tsarouhas, P. H., & Arvanitoyannis, I. S. (2010). Assessment of operation management for beer packaging line based on field failure data: A case study. *Journal of Food Engineering, 98*(1), 51-59.

Urban, T. L., & Chiang, W.-C. (2016). Designing energy-efficient serial production lines: the unpaced synchronous line-balancing problem. *European Journal of Operational Research, 248*, 789-801.

Verwaal, E. S. (2018). *Increasing efficiency of a production line by using protective capacity*. Delft: Delft University of Technology.

Vorne Industries. (2002-2008). *The Fast Guide to OEE*. Retrieved from www.vorne.com.

Webster, J., & Watson, R. T. (2002). Analyzing the past to prepare for the future: writing a literature review. *MIS Quarterly, 26*(2), 13-23.