Improving the Line Performance of Packaging Line 41 at Heineken Zoeterwoude

A CASE STUDY AT HEINEKEN

HEINEKEN

UNIVERSITY OF TWENTE.

Rutger J. Habets

“Tell me and I will forget, show me and I may remember; involve me and I will understand.”

- **Confucius**

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Bachelor project thesis on the improvement process of a packaging line: analytic- and performance- oriented perspective.

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Preface

After months of hard work, I am thrilled to present my graduation thesis for the BSc program: Industrial Engineering & Management. I especially would like to express my gratitude to some people. First of all, I would like to thank Daan van Leer for making this internship possible. Also, I want to thank my external supervisor, Liesbeth Bommer, for continuous support during my research. She encouraged me to think further by sparring with me and giving me feedback.

In addition, I would like to thank my first supervisor at the UT, Ipek Seyran Topan, for her flexibility and extensive evaluation sessions, which have helped me enormously in producing this work. Then, I would like to express my gratitude to Martijn Mes, my second supervisor at the UT, for his efforts and critical feedback in the final steps of this thesis.

Finally, I would like to thank my family and friends as they have supported me during this period.

For now, I would like to wish you a pleasant read. Best regards,

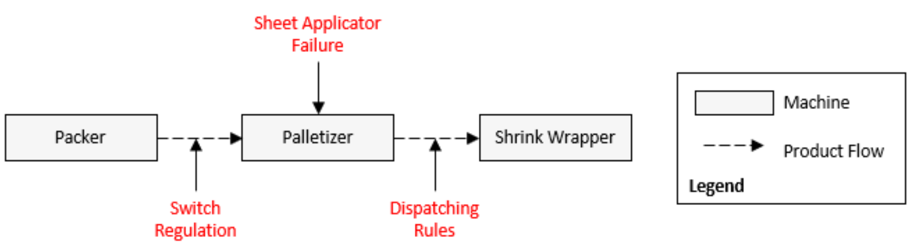
Rutger J. Habets

Executive Summary

Purpose – Heineken is a leading company in the beer market and aims to increase its dominance. In order to stay ahead of the competition, the group has to optimize all standards and reduce the losses caused by quality defects. This research focuses on *packaging line 41* on which the 5L tap barrels are packaged. The line performance should work as efficiently as possible to ensure high performance. However, an unregulated flow is created due to (external) failures, starvations or blockages. This leads to the main research question of this thesis: *How to improve line performance, by reducing the core bottleneck, of packaging line 41 at Heineken Zoeterwoude?* This study aims to improve the current line performance based on the principles of the *Theory of Constraints* (TOC), which is a systematical approach developed to earn more profit by increasing the throughput of a process or operation. In addition to line 41, this research also applies to *packaging line 42* as it is an identical line that faces the same problems. Therefore, this line is also taken into account in the cost analysis and conclusion.

Findings – According to the literature, a large amount of research has been conducted on *bottleneck analysis*. Based on these findings, data analysis has been performed to find the system's constraining machine, which is the weakest link. This analysis indicated the palletizer is the bottleneck. Therefore, the palletizer and adjacent processes have been thoroughly investigated to obtain deeper insights into current the problems. The results shows three potential points for improvement, which are visualized in the flow diagram below.

(1) <u>incorrect switch regulation</u> – The distribution of the conveyor switch's output pattern does not match the palletizer's input pattern. As a result, the palletizer becomes idle and blockage is caused on the packer;
(2) <u>frequently occurring sheet applicator failures</u> – The failure is occurring more frequently when poor material is used. This creates unregulated starts and stops which generate a non-continuous flow;
(3) <u>AGV dispatching rules</u> – Several scenarios have been faced, where the current AGV pickup priority could be improved. Incorrect decision making causes blockages at the machines upstream of the process.



In order to improve the line regulation, a *conceptual mod*el has been constructed representing the *steady-state* of the current system. It serves as the non-software description of the *simulation model*. This simulation has been created to find an alternative solution and, therefore, treats the points for improvement as experimental factors. A total of 17 experiments have been performed from which a suitable solution is found. The concluding paragraph of the executive summary further explains this solution. The table below compares the current situation with the alternative solution. It is visible the throughput is increased by **X** kegs (*confidential*) per hour during the system's steady-state.

Scenario	Throughput Line 41	
Current	**X** kegs *(confidential)*	
Alternative	**X** kegs *(confidential)*	
Difference	+**X** kegs *(confidential)*	*+3.22%*

Trade-offs – Trade-offs are made with regard to implementation of the alternative solution for both lines 41 and 42. The cost savings are expressed in *non-cash savings* and *cash savings* and contain €X (*confidential*) and €X (*confidential*) per year, respectively. In return, a one-off implementation fee of €X (*confidential*) euros has to be incurred. According to the Heineken principles, all investments made must be earned back within a time of two years. This investment meets this condition with a total saving of ***€X*** (*confidential*) in two years. Apart from that, (mental) health and safety are considered as well as a positive influence of the modifications is a more ergonomic and safer shop floor.

Conclusion – Finally, the improvement in line performance is expressed in OPI (*Operational Performance Indicator*) as this is the main *Key Performance Indicator* (KPI) of Heineken. By implementing the alternative solution, the performance is increased by **+ 1.57%** and **+ 1.58% OPI** for lines 41 and 42, respectively. Considering a working week during mid-season, this is equivalent to a reduced operating time of **209 minutes** per line. Regarding the alternative solution, it can be concluded that the line performance of both lines can be improved by:

- regulating the conveyor switch according to the dynamic settings. These settings exactly follow the stacking pattern of the palletizer;
- filtering out poor quality sheets and reducing the sheet applicator failure in this way;
- adjusting the *Automated Guided Vehicle* (AGV) pickup priority to the *Smallest Average Slack Time* (SAST) rule.

Recommendation – In addition to the recommendation to implement the alternative solution, some other inefficiencies and potential points for improvement are found during this study:

- Develop sense of ownership – Although Heineken is already focusing on creating ownership, it can be improved as employees do not always comply with their responsibilities nowadays. Moreover, it is also important to create awareness of the outcome of an action.
- Hire extra Pa-Pi engineers - Employees have to report inefficiencies by a label to comply with their ownership. However, there are not enough Pa-/Pi engineers to tackle the growing amount of labels which is considered demotivating. In addition, it is recommended to provide more insights into the waiting time once a label is created since this provides more understanding.
- Develop interdepartmental communication: Heineken should focus more on interdepartmental communication as it will create added value by knowing each other's role in the chain. This is really critical since the packaging and palletization department work separately, however, they have a large effect on each other. Therefore, Heineken should especially encourage peer-to-peer communication by bringing its employees together.
- Improve data registration at MES: The data registration system MES should be improved based on both accuracy and gaining more insight through providing extra parameters. Moreover, it is relevant to increase the understanding among employees regarding the usefulness of entering data.

- Optimize overall line balance: It is clear that the v-graph principle is not properly applied to the current system as it does not ensure products at the infeed and space at the discharge of the critical machine. Therefore, it is recommended to revise and where possible improve the current line balance with regard to buffer and capacity modifications.
- Improve performance of shrink wrapper: From the simulation study, it is evident a large amount of time is wasted due to failures at the shrink wrapper. As the shrink wrapper is the meeting point of three production lines, Heineken can improve the overall system performance by focusing on this machine.

Table of Content

Abbreviations

AGV	Automated Guided Vehicle
CS&L	Customer Service & Logistics
DBR	Drum-Buffer-Rope
HNL	Heineken Netherlands
HNS	Heineken Netherland Supply
KPI	Key Performance Indicator
MER	Mean Effective Rate
MES	Manufacturing Execution System
MSER	Mean Standard Error Rule
MTBF	Mean Time Between Failure
MTBS	Mean Time Between Starvation
MTOS	Mean Time of Starvation
MTTR	Mean Time To Repair
OEE	Overall Equipment Effectiveness
OPI	Operational Performance Indicators
OPI NONA	Operational Performance Indicator: No Orders, No Activity
TOC	Theory of Constraints
TPM	Total Productive Management

Dispatching rules:

FIFO	first in, first out
GWTIQ	greatest waiting time in queue
LD	longest distance
SAST	shortest average slack time
SAST + LACP	shortest average slack time + look-ahead control procedure
SD	shortest distance
SPTF	shortest processing time first

1 Research Introduction

This section serves as global introduction to the research performed at Heineken Zoeterwoude to complete my Bachelor project thesis of the study Industrial Engineering and Management. This work analyzes the efficiency of packaging line 41 in order to improve the current performance. In Section 1.1, the background information about Heineken and the brewery in Zoeterwoude is offered followed by the motivation for this study in Section 1.2. Then, the problem and objective are described in Section 1.3, whereafter the scope of the investigation is defined in Section 1.4. Subsequently, the research setup is defined in Section 1.5 including sub-questions and approach. Thereafter, the research methods are appointed in Section 1.6. Lastly, the main deliverables presented in Section 1.7.

1.1 Introduction to Heineken

Heineken NV is a Dutch brewing company, established in 1864 by the Heineken family. The group owns over 165 breweries in more than 70 countries, making them the world's most international brewer. With a team of more than 80,000 employees, Heineken posted a net revenue of €22,471 million in 2018 (Ede, 2008; Heineken N.V., 2019). Sales volume included around 233.8 million hectoliters, making the company one of the world's leading brewers.

In total, Heineken brews and sells more than 300 regional, local, international and specialty beers and ciders. Heineken® is the flagship brand and other international brands include Amstel, Desperados, Sol, Tiger, Tecate, Red Stripe, Krušovice and Birra Moretti. With this large portfolio, Heineken is currently the number one brewer of Europe and number two in the world.

In the Netherlands, The Heineken Company has three breweries, eight regional offices and one soft drink concern. Its beer production takes place in the breweries in Zoeterwoude, Den Bosch and Wijlre. This research study is conducted in Zoeterwoude, its largest brewery in Europe. Figure 1.1 shows the aerial view of this very advanced brewery. In Zoeterwoude, the annual production of Heineken® Beer is around ten million hectoliters, which is forty percent of the total volume. Therefore, more than sixty-five percent of this production is exported abroad.

Fig. 1.1: Heineken Zoeterwoude.

Fig. 1.2: 5L tap barrel.

1.1.1 Introduction to Heineken Zoeterwoude

Heineken Zoeterwoude is subdivided into two divisions: *Heineken Netherlands* (HNL) and *Heineken Netherlands Supply* (HNS). This study focusses on HNS, from which the organizational chart is shown in Figure 1.3. Here, the organizational structure for rayon 4 has been broken down into more detail as this study has been conducted in this department. My external supervisor, *Liesbeth Bommer*, is the manager of this rayon. Here, three shifts of operators work on the four packaging lines. These run on average seven days a week and sixteen to twenty-four hours per day. Four types of material are packaged on these lines; the brewlock, blade, can and 5L tap barrel. This work focuses on *packaging line 41* on which only the *5L tap barrels* (see Figure 1.2.) are packaged.

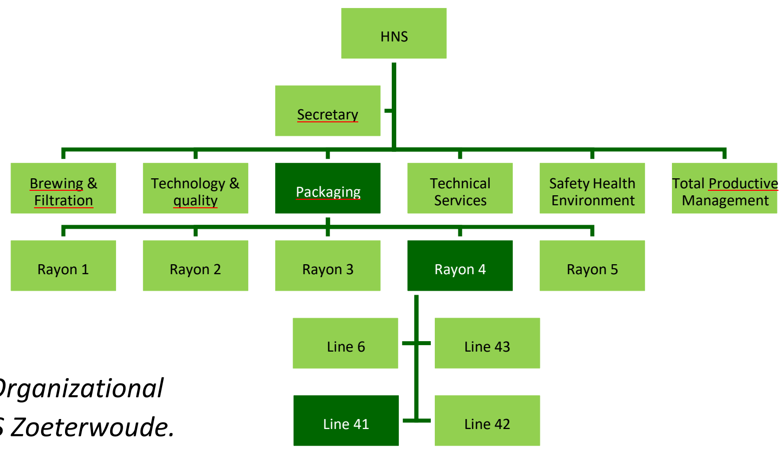


Fig. 1.3: Organizational chart HNS Zoeterwoude.

1.2 Research Motivation

There is an intense competition within the beer market, where price and innovation are the determining factors for success. Heineken is a leading company in this branch and aims to increase its dominance (Heineken N.V., 2019). It wants to stay ahead of the competition by *"optimizing all standards and reducing losses caused by quality defects"* (HNS, 2019)[1]. In other words, the company is striving for continuous improvement of its performance by using *Total Productive Management* (TPM). The TPM methodology is Heineken's tailor-made variant of Total Productive Maintenance, which is a systematical management philosophy aimed at maximizing performance by eliminating all breakdowns and defects (Nakajima, 1998). Through this method, productivity and quality are dramatically improved while the costs are reduced.

An increased and stabile performance positively influences the reliability as well. The reliability of machinery is incredibly important in order to adopt mass customization and rapid response strategies (Chu-Hua Kuei & Madu, 2003). Moreover, Heineken has to meet customer demand and therefore cannot afford any delays, breakdowns or slowdowns of the process. Such failures can be harmful to customer relationships.

An improved performance is also in line with the goal of HNS to become a global leader in sustainability in 2030. A sustainable company contributes to sustainable development by simultaneously contributing to economic, social and environmental benefits, which can also be termed as the *triple bottom line* or *3BL*

[1] The source is retrieved from Heineken's internal documents (not publicly available).

(Markley & Davis, 2007). The triple bottom line becomes increasingly important for organizations as environmental standards arise and incomes increase. In addition to social responsibility, the 3BL can be seen as a business strategy because huge profits can be achieved. Therefore, Heineken can significantly increase its competitiveness by engaging activities including reduction in obsolescence, waste, maintenance and repairs.

1.3 Research Problem Statement

It can be concluded from Section 1.2 that continuous improvement is a never-ending process, which is crucial to the success of a company. The key to success is the fact that this vision is implemented throughout the entire organization. Similarly on packaging line 41, where this research study has been conducted.

Line 41 consists of several machines that are connected to each other by conveyors which function by design as buffers according to the *v-graph principle*. The v-graph has been explained in more detail in Section 2.3. The machinery should work as efficiently as possible to ensure high performance. However, the packaging process stops due to (external) failures, starvations or blockages. The most interventions occur on the line between the tray-packer machine and pallet shrink-wrapper. This area is marked in red in Figure 1.5. The irregularities create a noncontinuous flow which generates unregulated starts and stops. This is the core problem of this research. In Figure 1.4, these cause and effect relationships are visualized more structured.

Outdated draft data shows the pallet shrink-wrapper and palletizer could be the bottlenecks in this process. This is mainly indicated due to the following two problems:

1. When the packaging line is operating at nominal speed and full efficiency, these machines do not meet the required capacity to go along with the process.
2. Breakdowns occur when the machines are operational.

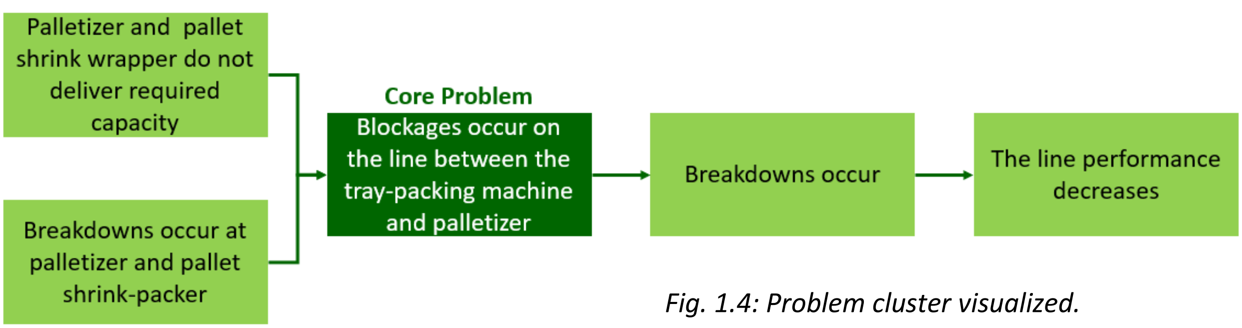


Fig. 1.4: Problem cluster visualized.

Heineken's line performance is indicated according to the *Operational Performance Indicator* (OPI), which is described in more detail in Section 3.1. It is similar to the *Overall Equipment Effectiveness* (OEE), and thus determined as a product of the availability, performance and quality (see Section 2.1). According to the literature, this *Key Performance Indicator* (KPI) is considered as the gold standard for measuring manufacturing productivity of continuous improvement processes (Gupta & Garg, 2012). This is in line with Heinekens TPM philosophy. Multiple studies indicate that the norm of a world-class OEE is considered to be 85% (Gupta & Garg, 2012; Vorne, 2002). Considering this norm, it is important to take in mind that the value is based on a particular country, industry and time (see Section 2.1). Although by using world-class OEE as a benchmark to compare the current OPI of packaging line 41, it can be concluded that there is room for improvement as it is 54% at this moment.

Therefore, the goal and action problem of this study is to improve the current OPI through line performance optimization. It is with this in mind that this thesis aims to answer the following research question:

Research Question

How to improve line performance, by reducing the core bottleneck, of packaging line 41 at Heineken Zoeterwoude?

It is requested by the management to gain thorough insights into the current losses in order to determine the machine efficiency relations. Apart from line 41, this research also applies to *packaging line 42* as it is an identical line that faces the same problems. Although this work mainly focusses on line 41, packaging line 42 is also taken into account during the alternative solution, trade-offs and conclusion as it is relevant for the management. In addition, Heineken wants advice on how to improve the packaging line performance. The management is interested in a recommendation regarding the most effective modification and its influence on line efficiency.

1.4 Research Scope

As mentioned before, this study focusses on packaging line 41, including associated employees, of the Heineken brewery in Zoeterwoude. The line starts at the depalletizer and ends with the pallet shrink wrapper. As described in Section 1.3, the most breakdowns occur between the packing machine and shrink wrapper (see Figure 1.5). Besides, previous research has shown that the pallet shrink-wrapper and palletizer behave as weak links in the system. This makes the management particularly interested in these work stations and its influence on the overall line efficiency. Therefore, the scope of this thesis is especially around this area. It is relevant to notice that the work stations upstream these bottleneck machines belong to the packaging department, while the palletizer and shrink wrapper are part of the palletization department instead. This means there are two principal stakeholders in this study (due to the overlap) which makes extensive cooperation crucial during the investigation.

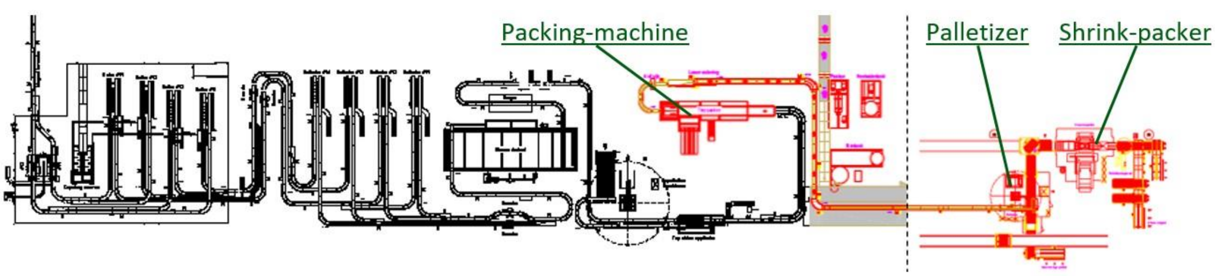


Fig. 1.5: Layout of packaging line 41; excluding the depalletizer. The dotted line is the split between the packaging- (left) and palletization (right) department. The critical area is marked in red (HNS, n.d.).[2]

[2] The source is retrieved from Heineken's internal documents (not publicly available).

A limitation of this research is that only the packaging lines are considered in this research. This has been decided as the external failures/factors, such as *Customer Service & Logistics* (CS&L), cannot be controlled in this study. An example is the blockage caused by a too slow transportation. This decreases the line performance, even when all machine are efficiently operating. In addition to the external factors, the planned downtime is out of scope as this study focusses on the steady-state of the production process. Another limitation to this research is that an improved performance of line 41 must not be at the expense of another line. Regarding the trade-offs it is relevant that all investments made must be earned back within a time of two years as this is a principle of Heineken. Over time, it is possible that the current research scope is redefined due to more insights in the problem. This process of fine-tuning is of utter importance because the shape, direction and progress of the research study is set (Andrews, 2003).

1.5 Research Setup and Approach

To successfully tackle the action problem, missing knowledge and information has to be acquired. Therefore, the problem statement (Section 1.3) has been divided into four pieces by using sub-questions. In this way, a better understanding of the options available for developing a successful research design can be created (Cooper & Schindler, 2014). These formulated questions function as the axis of the thesis and serve as a guide for the development of the theoretical framework, conceptual hypothesis and objective. In the description beneath the sub-questions, the approach is briefly described. The associated research methods can be found in Section 1.6.

1. What does the current system analysis look like?

a. How is the current packaging line organized?
b. What KPIs are currently used to measure performance?
c. Which current losses can be identified in the packaging line and what is the effect?
d. How can the causes of the core bottlenecks in the current process be found and what are these?

First, it is important to understand the packaging line in order to properly analyze the current situation. It is critical to know how the packaging processes are designed, monitored and controlled. Besides, deeper insights into the KPIs, that that are used to measure performance, are required as the improvement is measured regarding these KPIs. Once this basic information has been obtained, the current losses and its effects will be delineated and defined. Most of them can be found in Heineken's information system, however, not all are sufficiently visible. Afterward, the core bottleneck and corresponding causes and influences will be identified in order to determine the further direction of the study.

2. What alternative theories and tools are suggested in the literature for improving line performance by solving bottlenecks? What is the most suited approach for Heineken?

Prior to this research study, a systematic literature review on production line optimization methodologies has been conducted with regard to solving bottlenecks. By analyzing these methodologies, the following line improvement theories have been selected: *Total Productive Maintenance, Six Sigma, Lean manufacturing* and *Theory of Constraints*. Based on this selection of divergent theories, the literature review mainly focusses on the Theory of Constraints as it is the most appropriate method for this study: The theory aims to earn more profit by increasing the throughput of a process or operation. In addition, the literature will be consulted to find suitable tools for tracing and analyzing bottlenecks. Based on these results, this study formulates and applies the most appropriate tools to tackle the research problem.

3. How can the factors which influence the line performance be implemented in a simulation model?

a. What simplifications and assumptions can be made, and what is the influence?
b. What data are required for the model?
c. Which different scenarios will be experimented in the simulation study?
d. Wat techniques should be used to verify and validate both the conceptual and simulation model?

Thirdly, a *conceptual model* of the packaging line is required to develop a *simulation model*. A simulation is simplification of the reality created to predict the effect of changes in a system (Andradóttir et al., 1997). It has advantages for this research as there is a visual presentation of the solution in detail for the packaging line. This demonstration can be seen as convincing proof of the theory provided. In addition, several KPIs can be implemented and different scenarios can be tested and compared.

The selected methods from the research study will be implemented in the simulation study. To make an efficient and structured model, assumptions and simplifications have to be made at first. The stakeholders from Heineken will be asked for confirmation. Thereafter, the variables and data that are being used in the simulation model will be determined. This will consist of the information found in the second sub-question. Finally, output data has to be created in order to judge the performance. Besides, there will be a verification and validation of the model to make sure the model is designed with sufficient precision.

4. What recommendations are most beneficial to increase the performance of line 41?

a. What are the results, trade-offs, conclusions and recommendations of the simulation study?
b. What are the possibilities for improvement and consequences in terms of operating times, ergonomics and costs?

In the last phase of the research, the outcomes of the simulation study will be analyzed. Based on these results, a conclusion will be drawn and a recommendation delivered regarding further research and improvements.

1.6 Research Methodology

This steady used several research methods in order to answer the knowledge questions and successfully conduct the investigation.

To answer the first sub-question, the available knowledge at Heineken will be used in particular. A large amount of information will be gathered through conducting interviews with the line operators, supervisors and experts as they have the most knowledge of the line. By doing observations (empirical research) on the line, the design of the packaging line and machine functions can be identified. The losses and bottlenecks will be identified by doing quantitative research. The data will be acquired by the information system MES, which stores all relevant line and process data. This data have to be imported to Excel in order to find patterns by data analysis methods, such as analyzing graphs and pivot tables. The results will be reliable as this will concern real data over the past six years, which will be thoroughly validated. The data will be observed on source, patterns and modifications. In addition, the packaging process will be recorded by camera, tracked by stopwatch and empirical observed. Thereby, experts (e.g., machine owners) and internal documents (e.g., maintenance manuals) will be consulted for validation.

Besides, more knowledge in detecting bottlenecks will be obtained by applying the literature since several studies have been done on this. The answers of the second sub-question will be collected through a (systematic) literature review as well. Multiple literately sources will be analyzed in order to collect the required information by using different databases. As mentioned earlier, this research will start with a broad scope by analyzing three divergent methodologies: Six Sigma, Lean manufacturing and Theory of Constraints. However, this will be narrowed as research progresses since the direction of the solution can be better determined. Further research will be focused on the most suited philosophy in order to find the most appropriate approach.

The simulation model, mentioned in sub-question 3, will be designed by expertise and literature. The simplifications, data and variables of the model will be determined by conducting interviews with operators and supervisors. The data and variables will also be created by the information collected in the first phase of the research. This model will be validated according to white-box validation as it advised by Robinson (2004). With white-box validation, the conceptual model is compared to the real-word by checking the code, performing visual checks and inspecting output reports. The code will be checked by showing the model to the team and critically discussing it with operators and the manager. In addition the verification of the model will be completed through continuously debugging and checking the simulation. The logic of the code will be examined with the help of experts as the secondary supervisor and the output will be compared with the KPIs of the production line. In this way, the reliability of the results will be guaranteed. In terms of external validity, the execution of in this research can be applied to similar scenarios as this is a case study. These situations will contain production lines with bottleneck problems.

Finally, the trade-offs, conclusion and recommendations will be provided based on the results. The outcomes will be discussed with the operators and experts at Heineken. It is important to take the interests of these stakeholders into account.

In Figure 1.6, a summary of the research methods and the relationships is shown. Here, the distinction is clearly visible what information will be gathered from the literature and Heineken.

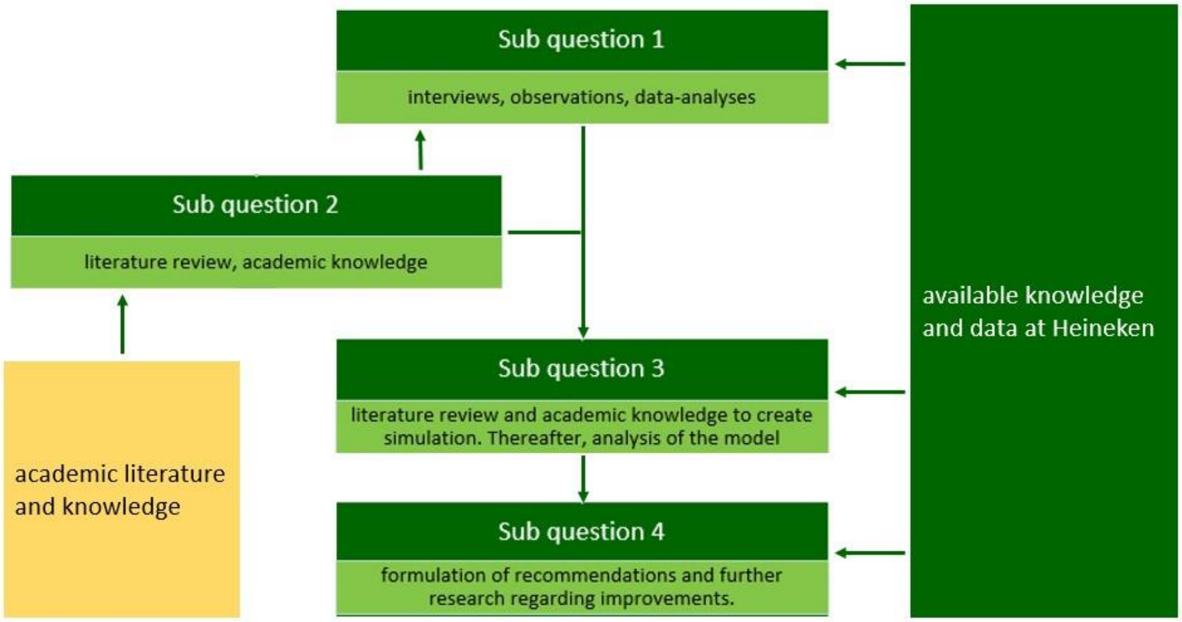


Fig. 1.6: Structured cluster of research methods used and the relationships.

1.7 Research Deliverables

At the end of this research, the following deliverables will be presented:

a. A current system analysis of the packaging line.
b. Both a conceptual and simulation model which give insights in the impact of the improvement methods and accompanying manual.
c. An advice regarding improvements of the packaging line and further research.

2 Literature Review

This section contains the literature review, which serves as the theoretical framework for this research study. In Section 2.1, the concept of Total Productive Management, Heineken's improvement strategy, is explained to get a deeper understanding of the implemented operations strategies at Heineken. Thereafter in Section 2.2, the Theory of Constraints, including opportunities, is explained because it serves as the guiding strategy of this research. Moreover, the theory behind the data analysis is described in Section 2.3, followed by a set of dispatching rules in Section 2.4. Finally, the theoretical framework behind the simulation model is provided in Section 2.5.

2.1 Operations Management Strategy: Total Productive Management

A number of strategies have surfaced in the organizational movement, aiming to manage and continuously improve operational performance to achieve world-class product/service quality and market success (Kumar, Maiti, & Gunasekaran, 2018). This can be explained as the emphasis amongst operations professionals has shifted towards making improvement one of their main responsibilities (Slack, Chambers, & Johnston, 2010).

2.1.1 Definition of Total Productive Management

Heineken has been implementing Total Productive Management (TPM) since 2006, when it was introduced at their production facilities. It is a symbiosis of Lean (Krafcik, 1988), Six Sigma (Smith, 1993) and Total Productive Maintenance (Nakajima, 1988). These three strategies are briefly explained to understand their different perspectives. The leading methodology is the Total Productive Maintenance ideology, which is a systematical management philosophy aimed at maximizing performance by eliminating all breakdowns and defects (Nakajima, 1998). Heineken has particularly chosen for this continuous improvement program as it believes creating ownership will be a key factor in the company's success. From this point of view, the main objectives are to achieve zero failures, zero defects and improved output by increasing operator participation and ownership (Kulkarni & Dabade, 2013). The program has been implemented by using lean tools to reduce waste on the job-floor of its operations, which complies with the principles of Total Productive Maintenance. Nowadays, the philosophy has been adopted in the entire organization.

It is important to emphasize on the fact that the initials of Total Productive Maintenance and Total Productive Management are the same (both TPM). However, they both refer to another notion. In this thesis (excluding Section 2.1.4), the abbreviation TPM will always refer to Total Productive Management; Heineken's continuous improvement methodology. Therefore, the term Total Productive Maintenance will not be abbreviated in this report.

2.1.2 Definition of Lean Manufacturing

The principles of Lean Manufacturing (LM) are derived from the Toyota manufacturing system. The term lean was first coined by John Krafcik (1988) in his article, *Triumph of the Lean Production System*. Lean techniques are used in all manufacturing industries and aim to produce Just-In-Time (JIT) while creating value for consumers using the least resources (Ng, Vail, Thomas, & Schmidt, 2010). The principles are focused on creating standardized work in order to smooth out the workflow by continuously eliminating problems and wasteful activities. According to Slack and his colleagues (2010) "Murda" (waste) is evident in all non-value adding steps in a process, such as over-stock inventories, badly sited machines, overproduction and so on. When people learn to identify and eliminate waste, both, production and quality increase as a result (Adams, Componation, Czarnecki, & Schroer, 1999).

2.1.3 Definition of Six Sigma

Six Sigma is a continuous improvement methodology that was originally developed by Motorola in 1987. Their initial goal was to reduce the number of manufacturing defects to 3.4 parts per million (Barney, 2002). The name of the concept finds its origin in the specification range of any part of a product or service, which should be ±6 the standard deviation of the process (Slack et al., 2010). Nowadays, the definition of this concept has widened to well beyond this narrow statistical perspective. According to General Electric (GE), who were one of the early adopters, the methodology can be defined as "*A disciplined methodology of defining, measuring, analyzing, improving, and controlling the quality in every one of the company's products, processes, and transactions – with the ultimate goal of virtually eliminating all defects.*" This implies the strategy can be integrated into organizations to reach strategic objectives by reducing variation in certain processes.

2.1.4 Definition of Total Productive Maintenance

In 1988, the principles of the Total Productive Maintenance (TPM) system were first published in English by Nakajima (1988) in his article *Introduction to Total Productive Maintenance*. According to the literature, TPM is considered as an integrated life-cycle approach for organizations to transform their manufacturing facility into a world-class production environment (Blanchard, 1997; Hooi & Leong, 2017). Afefy (2013) describes the strategy as an aggressive maintenance policy that focusses on improving the function and design of production equipment. The methodology aims to maximize equipment effectiveness by applying a comprehensive preventive maintenance system covering the entire life of equipment, spanning all equipment-related fields and increasing employee morale and job satisfaction (Venkatesh, 1996; Afefy, 2013). TPM is implemented by various departments in a company and builds a sense of ownership by totality involvement in small group activities (Nakajima, 1988; Hooi & Leong, 2017). Operators will become more pride and responsible because TPM creates an environment where people are given authority, resources and time to make sound decisions (Kulkarni & Dabade, 2013). Through creating this sense of ownership, the methodology cuts the operating and maintenance costs by concentrating on the causes of failures.

2.1.5 Performance Indicator: Overall Equipment Efficiency

Based on the TPM philosophy as proposed by Nakajima, Semiconductor Equipment and Materials International (SEMI) has developed the Overall Equipment Efficiency (OEE). This metric is entirely expressed in time and serves as a standard for measurement and definition of equipment productivity (De Ron & Rooda, 2005). In considering OEE, six equipment losses have been defined by Nakajima (1988): equipment failure, setup and adjustment, idling and minor stoppage, reduced speed, defects in the process and reduces yield. Based on these losses, OEE is calculated as a product of the availability of the equipment, performance efficiency of the process and rate of quality products as is shown in the equation below (Afefy, 2013).

$$OEE = Availability * Performance\ efficiency * Rate\ of\ Quality$$

The OEE measure can be applied at several different levels within a production environment. For instance, it can be used on machine level, on a manufacturing line, or as a " benchmark" for measuring the initial performance of an entire manufacturing plant (Bamber, Castka, Sharp, & Motara, 2003). Based on practical experience, "world-class" OEE numbers have been defined by Nakajima (1988). Table 2.1 presents these numbers. Considering these numbers, it is important to take in mind that these numbers have roots in a particular place (Japan), at a particular time (1970s), and in a particular industry (automotive) (Vorne, 2002).

Table 2.1: The Percentage of World Class OEE.

Criterion	**World-Class Number**
Availability	90%
Performance	95%
Quality	99%
Overall Equipment Efficiency (OEE)	85%

2.2 Operations Management Strategy: Theory of Constraints

The Theory of Constraints (TOC) has been developed and first published by Eliyahu Goldratt (1984) in his novel *The Goal*. The overall objective is to earn more profit by increasing the throughput of a process or operation (Slack et al., 2010). As *The Goal* (1984) states, one can drastically increase performance by actively focusing on and controlling the bottlenecks of the system. Goldratt indicates: *"An hour lost at a bottleneck is an hour lost for the entire system."*. This means a bottleneck should work at all times as it is the weakest link in the system. Slack and his colleagues (2010) argue it is sensible to keep a buffer of inventory in front of the constraint to make sure it always has something to work on. According to Eli Goldratt, the underlying premise of the theory is that an organization can be measured and controlled by variations on the following three measures:

1. Throughput defined as sales revenue less totally variable costs.
2. Inventory defined as all investments that can be converted to cash.
3. Operating expense defined as all costs that have to be incurred to convert inventory to throughput.

The TOC consists of a systematical approach emphasizing five sequential steps. To quote Goldratt, these steps are defined as:

1. Identify the system's constraint(s).
2. Decide how to exploit the system's constraint(s).
3. Subordinate everything else to the above constraint(s).
4. Elevate the system's constraint(s).
5. Warning! If in the previous steps a constraint has been broken, go back to step 1, but do not allow inertia to cause a system's constraint.

2.2.1 Effectiveness of Theory of Constraints

Mabin and Balderstone (2003), conducted a case survey analysis, which draws on 81 published case studies relevant to TOC application. It is important to take comfort in the fact that TOC is founded on systems principles, mainly focusing on the big picture and local practices on overall performance. The results do not show too much of negative critique on the theory apart from some limitations. For instance, it can be difficult to control all constraints or difficult to handle uncontrollable constraints (AccountingForManagement.org, 2012). On the other hand, numerous success stories are reported by organizations, indicating that TOC did provide a substantial source of competitive advantage (Mabin & Balderstone, 2003). Applying this theory gained considerable improvement in critical performance measures, including lead time, cycle-time, throughput and profits.

2.3 Theory Behind the Data Analysis

This section explains the theoretical framework of the data analysis. The paragraph contains a description of bottleneck detection methods that have been used as the applied bottleneck analysis techniques in this research study.

2.3.1 Bottleneck detection: Turning-Point Methodology

The "turning-point" methodology is a bottleneck detection approach focusing on the machine states. This method is a data-driven technique for throughput bottleneck detection. The underlying idea of this method is to utilize the production line's blockage and starvation probabilities to find the core constraint(s) in a system (Kuo, Lim, & Meerkov, 1996; Li, Chang, & Ni, 2009). According to Li, Chang, Ni, Xiao and Biller (2007), the approach is based on the assumption that the bottleneck machine is least affected by other machines in the system. This ideology leads the way to a bottleneck by comparing the operations of two adjacent machines. Hence, if the blockage time of the upstream machine is higher than the starvation time of the subsequent machine, the bottleneck must be downstream; otherwise, the bottleneck is located upstream. Usually, a bottleneck machine will also have al higher overall sum of blockage and starvation time. Based on these characteristics Li and his colleagues defined the "turning point" as the machine where the trend of blockage and starvation changes. This phenomenon has been illustrated in Figure 2.1.

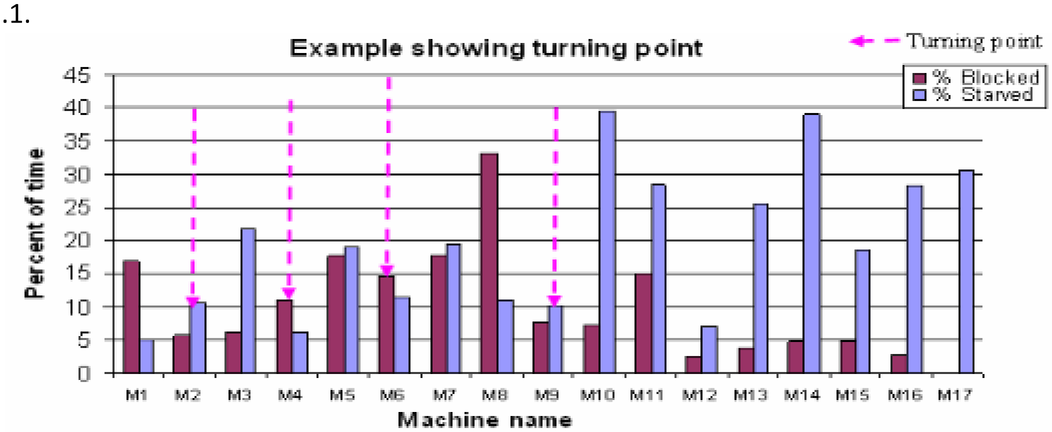


Fig. 2.1: Case to show turning points are determined (Li et al., 2007).

For the special case that no turning point is identified, the bottleneck will be the first machine if each machine's starvation is higher than its blockage; else the last machine will be the bottleneck as the blockage for all machines is the most dominant state. The approach can be described as an "arrow-based" method as the arrows between the adjacent machines indicate the direction of a bottleneck (Kuo et al., 1996; Li et al., 2009).

2.3.2 Bottleneck detection: V-Graph Methodology

Heineken has implemented the theory of the V-graph in all its production lines, which is a buffer strategy used to optimize line performance (Härte, 1997). Every line has a critical machine, which is usually the slowest machine (Härte, 1997; Optimumfx, 2018). As the production chain is never stronger than its weakest link (Goldratt & Cox, 1984) and losses made by the bottleneck cannot be corrected by other machines, it is this methodology's objective to maximize capacity on either side of the core machine in the assembly line. This ensures that the critical machine has products at its infeed and space at its discharge. Due to overcapacity on either side, the accumulation can be restored after a breakdown on the line occurs. Therefore, the conveyers upstream the core machine should be filled with products and buffers downstream should be empty (see Figure 2.2).

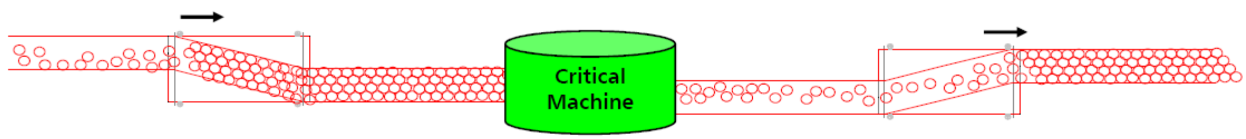


Fig. 2.2: Ideal conveyer flow at the critical machine (HNS, 2017)

The v-graph principle is implemented throughout the entire production line. Machines upstream the process have extra capacity with respect to the next, and machines downstream with respect to the previous work station. This creates the V-shape when plotting the line's production capacity in a graph as is visualized in Figure 2.3. The slope of the V-graph is correlated to the machine reliability as the V-graph methodology is a buffer strategy. According to Härte (1997), this implies that the V-shape may become (more) flat, as the reliability of the installations improves, making buffers obsolete.

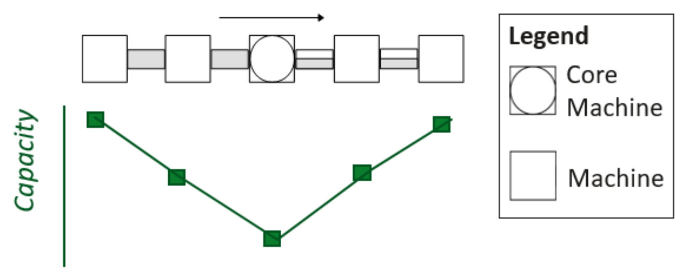


Fig. 2.3: Representation of the V-Graph (Härte, 1997)

By analyzing the v-graph theory, the bottleneck of a system can be identified. Therefore, Härte also introduced the *Mean Effective Rate* (MER) in order to determine the bottleneck machine in a packaging process. The MER can be calculated by the following equation:

$$\boldsymbol{MER} = \frac{Production\ Time}{Production\ Time + Failure\ Time} * Machine\ Capacity$$

The production time divided by the production time plus the failure time is the actual time that the machine could produce, or in other words: the availability. The machine containing the lowest MER value usually is the bottleneck machine. Figure 2.4 illustrates a certain v-graph, where the pasteurizer is the core machine based on its capacity. However, the rinser/filler behaves as the bottleneck machine, which is visible by looking at the MER.

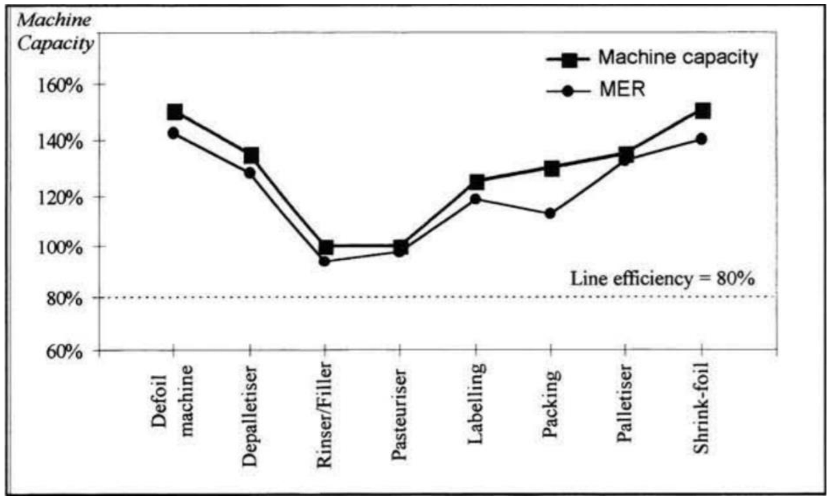


Fig. 2.4: V-graph including machine capacities, MER and Line efficiency (Härte, 1997).

2.3.3 Bottleneck Analysis: Pareto Analysis

Vilfredo Pareto was a late nineteenth-century economist, who first noted that 80% of the wealth in Italy was owned by 20% of the population (Sanders, 1987). This is the basis of the "Pareto law" or the "80/20 rule", which is a power-law probability distribution (Ehrgott, 2012). Lande, Shrivastava and Seth (2016), state, one can use the tool as a very successful technique carrying out problem-solving methods in manufacturing. The Pareto analysis is especially used in the selection of projects during the "define" phase and/or identification of vital errors while executing the "Analyze" phase. Based on the results, the root causes are then further analyzed in order to solve the problem. According to Lande and her colleagues, the 80/20 rule usually serves as a guide to improve a process.

2.3.4 Bottleneck Analysis: Ishikawa-Diagram

The Ishikawa diagram is a tool that can be used to organize and display relationships (Garvin, 1993). The diagram owes its name since it has been developed by Kaoru Ishikawa. It is also commonly referred to as the fishbone diagram because of its structural outlook and appearance (see Figure 2.5). By its design, it evaluates the (possible) causes and sub-causes of one particular problem and therefore assists to uncover all the symptoms (Bose, 2012). According to Slack et al. (2010), often the subdivision of possible causes is made of the rather old-fashioned headings: machinery, manpower, materials, methods, and money. In practice, however, all relevant possible causes could be used. For its cause and effect structure, the tool is termed as a "cause-effect diagram": a systematic questioning technique for searching out the root cause of problems.

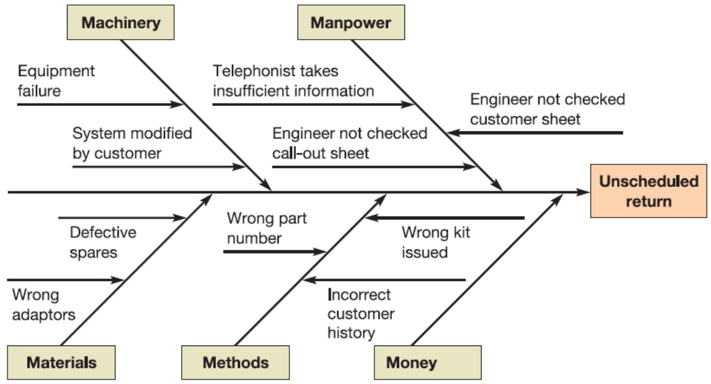


Fig. 2.5: Ishikawa diagram of unscheduled returns at KPS (Slack et al., 2010).

Garvin (1993) states, one should also include a data analysis to verify assumed relationships because brainstorming alone is based primarily on hunches and personal experiences. Substantiating assumptions with data ensures that the right elements have been targeted. In addition, it will provide information about the effectiveness of the countermeasure.

2.3.5 Bottleneck Analysis: Gemba

Gemba is a Japanese term that means "the actual place" where a process happens. The technique is often used in the lean or improvement philosophies to convey the idea, one should visit the work floor in order to understand the actual process (Simona & Cristina, 2015). Mann (2009) defines the walk as a three-part rule: 1. Go to the place. 2. Look at the process. 3. Talk with the people. If a quality problem occurs in a manufacturing environment, engineers and the technical team should "go to Gemba" (Nestle, 2013). The same goes for a manager. Simona and Cristina (2015) discuss, an executive should regularly visit the floor to gain a true appreciation of the realities of improvement opportunities.

2.4 Dispatching Rules

There has been a rapid advance of automation in the manufacturing environment as 20% to 50% of operational cost can be attributed to material handling (Ho & Chien, 2006). As a result, numerous automatic guided vehicle (AGV) applications have been reported because it is the most flexible system due to their routing flexibility according to many industrial engineers. Many researchers have studied various AGV-related problems including the popular approach of using dispatching rules. Ho and Chien recommend dispatching rules as advantageous and "easy to use". This is highly important for dispatching AGVs, which often requires real-time decision making. A large number of researchers, including Rajendran and Holthaus (1999), Ho and Chien (2006), and Ying-Chin Ho and Liu (2019) have created a selection of dispatching rules. Based on these findings, the most appropriate single-load AGV dispatching rules are listed in Section 2.4.2. A finding is considered relevant when it is applicable in the current system. Therefore, dispatching rules focused on multi-load and multiple AGVs, due date, and remaining work is excluded.

2.4.1 Terminology of the Dispatching Rules

Before, the selection of dispatching rules is presented, the terminology used in this section is introduced. Let

TB_b time of arrival of a part at buffer b;
TE_b time of arrival of a part at the output of buffer b;
PT_m processing time of a part at machine m;
BT_m remaining time that the process can be delayed until machine m is blocked;
TX_{mb} AGV travelling time from machine output-buffer m to machine input-buffer n;
TX_{bm} AGV travelling time from machine input-buffer n to machine output-buffer m;
TL AGV loading time;
TU AGV unloading time;
Z_i priority value assigned to job i at the time of decision of dispatching.

2.4.2 Selection of Dispatching Rules

A study of existing literature on dispatching rules reveals the following selection of dispatching rules, which are effective for different measurements. These rules will be briefly described according to their definitions in the literature.

(1) FIFO (first in, first out) rule: According to the Rajendran and Holthaus (1999), this rule is often used as a bench-mark. Using this rule, the priority value is assigned to the job that has entered the output queue of machine m first. According to the authors, one should apply this rule for minimizing the maximum flowtime and variance of flowtime. The priority index of this rule is given by:

$$\boldsymbol{Z_i} = Min\ \{ TE_m \}$$

(2) SD (shortest distance) rule: If the shortest distance rule is used, an AGV gives priority to the nearest working station.[3] Le-Anh and De Koster (2005) state, shortest-travel-distance-first dispatching rules tend to have a good throughput performance in a single-attribute environment. Moreover, the authors discuss the pitfall of this rule. The station not near the vehicle release point can hardly qualify to receive a vehicle dispatch. Therefore, its success of implementation depends on the layout of facilities. The priority index is given as follows:

$$\boldsymbol{Z_i} = Min\ \{ TX_{mn} \}$$

(3) SPTF (shortest processing time first) rule: Rose (2001) defines, this discipline is a simple approach as the lot with the shortest processing at a particular workstation m is ranked first in priority. The rule is most effective in minimizing mean flow time and tardiness (Rajendran & Holthaus, 1999), and reduce cycle times under highly loaded shop floor conditions (Rose, 2001). The priority index is defined as follows:

$$\boldsymbol{Z_i} = Min\ \{ PT_m \}$$

[3] In contrast to the SD rule, the longest distance (LD) rule determines priority based on the longest distance.

(4) SAST (smallest average slack time) rule: Slack is the amount of time that an activity can be delayed without delaying the system (Jensen, Locke, & Tokuda, 1985; Rhee, Bae, & Kim, 2004). In this study, slack indicates the elapsed time to the critical time minus its estimated completion time. Therefore, using the SAST discipline, the AGV's destination is determined based on the workstation m with the smallest estimated slack. The rule is an effective approach for reducing bottlenecks and minimizing the variance of work delays (Rhee et al., 2004). Based on the description of Jensen et al. (1985), the following priority index is defined:

$$Z_i = Min \{ BT_m \}$$

(5) SAST + LACP (smallest average slack time + look-ahead control procedure) rule: Jang and Ferreira (2001) state, most of the dispatching rules are limited in using information of the expected or average behavior of the system. In their research, therefore, the authors focused on the future state of the SAST rule by using a look-ahead algorithm. LACP uses information such as the part's (un)loading time and AGV traveling time, which are obtained by look-ahead. Now the slack is calculated by subtracting these remaining processes from the estimated machine blockage time. The priority index is:

$$Z_i = Min \{ BT_m – TX_{mn} - TL – TX_{nm} – TU \}$$

(6) GWTIQ (greatest waiting time in queue) rule: Under this rule, the priority will be given to the part that has the greatest waiting time in the output queue of machine m (Ho & Liu, 2009). This approach aims to prevent parts from wasting excessive time in a buffer because they may hamper the entire production process (Klei & Kim, 1996). The priority index is formulated as follows:

$$Z_i = Min \{ TB_b \}$$

2.5 Simulation Study

This section of the literature study regarding the simulation is threefold. First, the general purpose of a conceptual model is described. Thereafter, several tools for creating a proper experimentation setup are explained, followed by a description of model verification and validation.

2.5.1 Conceptual Model of the Simulation

Robinson (2004) states that the conceptual model is the most important aspect of a simulation as the design impacts all aspects of the study. According to him, the conceptual model is defined as a non-software description of the simulation model consisting of the objectives, inputs, outputs, content assumptions and simplifications. This definition is established based on two key components. First, it identifies the independence of the model from the simulation software. Second, it outlines the six key pillars of the model. To quote Robinson, these are the following:

1. Objectives – the purpose of the model and modeling project.
2. Inputs – those elements of the model that can be changed to effect an improvement in, or a deeper understanding of, the real-world.
3. Outputs – report the results from simulation runs.
4. Content – the components that are presented in the model and their interconnections (e.g., scope and level of detail).

5. Assumptions – made either when there are uncertainties or beliefs about the real-world being modeled.
6. Simplifications – incorporated in the model to enable more rapid model development and use.

In general, the goal of a conceptual model should be to create a model as simple as possible to meet the objectives of the simulation study as a whole.

2.5.2 Experimental Setup of the Simulation Study

Through experimentation, a better understanding for improvement of the current system can be obtained. One should deal with initialization bias and obtain sufficient data to ensure that accurate results are received. However, the nature of simulations models and simulation output is explained at first.

Nature of the Model

According to Robinson (2004), the nature of the model is the first issue considered in the experimental setup as it affects the means in which accurate results are obtained. Taking the nature of the model into account, Altiok and Melamed (2010) conclude that the model is either terminating or non-terminating depending on the objectives of the study. A simulation is classified as terminating if there is a natural endpoint that determines the length of a run (e.g., empty system because the production shift is finished). Otherwise, the model is identified as non-terminating and the run-length needs to be determined by the user. Moreover, Robinson (2004) discusses four different types of simulation output:

(1) transient output – The distribution of the output is constantly changing. For instance, the number of customers served hourly in a bank.
(2) steady-state output – The output is varying according to some fixed distribution (the steady-state distribution). For instance, the daily throughput from a production line.
(3) Steady-state cycle – The output cycles through a pattern of steady-states, which likely occurs with a non-terminating model. For instance, a production plant containing three shifts, each with a different number of operators
(4) Shifting steady-state – The output shifts from one steady-state to another as time progress. For instance, the throughput at a supermarket due to varying cash register occupation.

Robinson (2004) states, the output of a terminating process is often transient and from non-terminating models is mainly steady-state (possibly with a cycle or shifts). To validate this, one should examine, both, the input and output data.

Initialization Bias

In order to examine the steady-state behavior of a system, the initialization bias needs to be removed from non-terminating simulations (Robinson, 2004). For terminating simulations this is usually not the case as these start from, and return to, an empty condition. According to Robinson, a suitable approach in handling this initialization is by applying a warm-up period (see Figure 2.6). Statistics will be collected after this initial period of system warm-up. From Robinson's summarization of methods for identifying initialization bias and determining the warm-up period. From this, the hybrid method appeared as a suited approach. This is an extended approach consisting of graphical and heuristics methods including an initialization bias test. In this study, the Marginal Standard Error Rule (MSER) has been used. This method aims to find a strong trend in the mean of the series by minimizing the width of the confidence interval about the mean of the simulation output data (Asmussen & Glynn, 2007; Mes, 2019)[4]. Below, the **MSER** as a function of the length **d** of the warm-up period is presented:

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

Where **m** is the total number of observations from the time series of output data and $\bar{\mathbf{Y}}(\mathbf{m},\mathbf{d})$ the mean from $\boldsymbol{Y_{d+1}}$ till $\boldsymbol{Y_m}$. Now, the length of the warm-up period can be calculated by the following equation:

$$\underset{n\,>\,d\,\geq\,0}{\arg\min}\ \boldsymbol{MSER\ (d)}$$

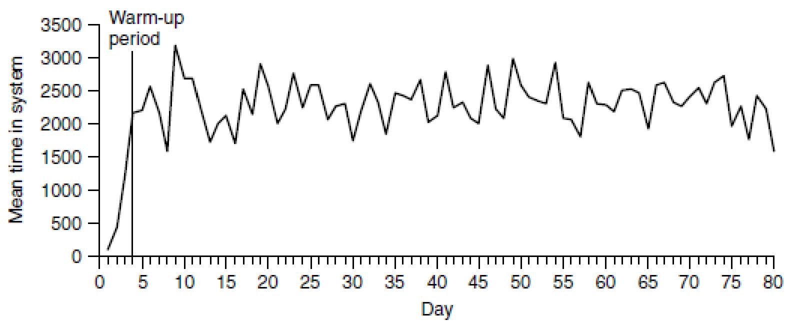


Fig. 2.6: Visualization of the warm-up period (Robinson, 2004).

Obtaining Sufficient Data

An appropriate run-length and number of replications should be performed to ensure that enough output data have been obtained (Robinson, 2004). Robinson explains one can execute multiple replications or a single long run. The advantage of performing multiple replications is that confidence intervals can easily be calculated. These indicate an important measure of the accuracy of the simulation's results. On the other hand, the warm-up period needs to be run for every replication performed which wastes experimentation time. The single long run is not further explained because it is not used in this research.

Multiple replications are performed by changing the seeds of the initial random number generator. The aim of this approach is to produce several samples to obtain a better estimate of mean performance. Robinson (2004) explains the rule of thumb, which recommends three to five replications are performed at least. Moreover, the recommended number of replications can specifically be determined by the application of the confidence interval method. According to the author, the confidence interval is defined as "a statistical means for showing how accurate the mean average value is being estimated". By applying this method, replications are performed until the interval becomes sufficiently narrow to satisfy the user. This might typically be at a level of less than 5%. The confidence interval **CI** can be calculated by the equation below:

$$\boldsymbol{CI} = \bar{X}\ \pm\ t_{n-1,\alpha/2}\frac{S}{\sqrt{n}}$$

[4] The second source between parentheses is retrieved from Canvas Utwente (not publicly available).

Where $\bar{X}$ is the mean and **S** is the standard deviation of the output data from the number of replications **n**, and $t_{n-1, \alpha/2}$ is the value from the user's t-distribution with **n-1** degrees of freedom and a significance level of **α/2**.

In addition to the number of replications, one also has to determine the run length of the simulation. Robinson states that this run length should be at least 10 times greater than the warm-up period.

2.5.3 Verification and Validation of the Simulation Study

Verification is the process of ensuring that the conceptual model has been transformed into a correct model with sufficient accuracy and has matched any agreed-upon specifications and assumptions (Carson, 2002). The verification process can be seen as a subset of the validation process, which is the procedure of evaluating whether the model is sufficiently accurate for its purpose (Robinson, 2004). Carson (2002) discusses the main goal of verification and validation – to create a reliable model to predict the performance of the real-world system (that it represents) under different circumstances. Both processes should be performed throughout the entire life-cycle of a simulation study.

Verification and White-Box Validation

Although verification and white-box testing are conceptually different, both topics are treated together here because white box-testing is often used for verification (Nidhra & Dondeti, 2012). Verification can be performed by the modeler alone and ensures that the model is true to the conceptual model (Robinson, 2004). White-box validation, on the other hand, is used to ensure that the content of the model is true to the real system and requires the involvement of those knowledgeable about the system in real-life. Based on the findings of Robinson, the following three methods of verification and white-box validation are discussed:

(1) checking the code – To continuously read through the model coding to ensure that the right data and logic have been entered. A debugger is often used to verify the program (Altiok & Melamed, 2010).
(2) visual checks – To run the model and watch how each element behaves, both the logic of the simulation and behavior against the real-world are considered. Moreover, it is recommended to demonstrate the model formally and informally to experts and those involved. This should enable them to identify any shortcomings and increase the credibility of the work. Other useful techniques are the following: stepping through the model event by event, predicting events and taking the results in consideration, tracing the progress of a certain part in the model, and experimenting by creating extreme conditions (e.g., extreme arrival rates) to determine whether the model behaves as expected.
(3) inspecting output results – To compare the performance of the individual elements (intrinsic) of the model to the actual results.

Black-Box Validation

White-box validation is intrinsic to model coding as described in the paragraph above (Robinson, 2004). On the other hand, black-box validation takes the overall behavior into account and, therefore, can only be performed once the model code is finished. Since the code is purely considered to be a "big black box", only information about the input and expected output are known to the user (Nidhra & Dondeti, 2012). Nidhra and Dondeti state, one should apply both white-box and black-box validation to test software more correctly. Robinson states, there are two broad approaches of black-box testing. Firstly, to compare the simulation to the real-world system. The other is to compare the simulation model to another model. The latter technique is not included in this literature study because it has not been applied in this research.

The first method of black-box validation is explained based on the schematic representation in Figure 2.7. The method aims to compare the simulation system to the real-world system by running it under the same conditions ($I_R = I_s$). As a result, the output should be sufficiently similar ($O_R \approx O_S$). While taking this output data into consideration, it is important to focus on the averages and spread of the data (standard deviation). One can place its confidence in a model by judging how closely these averages from the model and real-world data match.

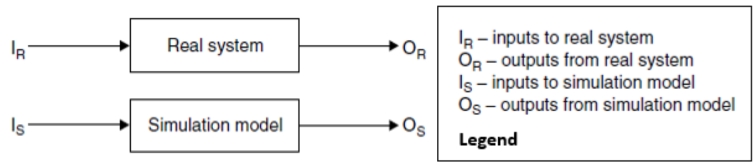


Fig. 2.7: Black-box validation: Comparison with the real system (Robinson, 2004).

2.6 Conclusion of the Literature Review

TPM is used by Heineken and considered as an integrated life-cycle approach for organizations to transform their manufacturing facility into a world-class production environment. Heineken has particularly chosen for this continuous improvement program as it is implemented by various departments in a company and builds a sense of ownership by totality involvement in small group activities.

The leading strategy of this research is the Theory of Constraints. It is a manufacturing method developed to increase performance by actively focusing on and controlling the bottlenecks of a system. The philosophy believes that *"an hour lost at a bottleneck is an hour lost for the entire system."*. The TOC provides a substantial source of competitive advantage according to the many success stories reported by organizations

According to the literature, the turning-point and v-graph methodology are two suitable data-driven methods for bottleneck detection. The turning-point method is an approach focusing on the machine states by utilizing the blockage and starvation probabilities to find the core constraint(s). The v-graph theory is a buffer strategy, implemented by Heineken, from which the MER (production time/availability) has been derived to determine the bottleneck location. The machine containing the lowest MER value is the constraining machine. Once the bottleneck is detected it can be further analyzed by conducting a Pareto analysis, establishing an Ishikawa-diagram, or "going to Gemba".

Furthermore, a direction for improving bottleneck performance is dispatching rules. Researchers have studied various automated guided vehicle applications including dispatching rules which are relatively easy to use. In this research study, dispatching rules regarding the following criteria have been applied: arrival time, travel distance, processing time, slack time, look-ahead control procedure, and waiting time in queue.

Finally, more insights on the construction of a conceptual and simulation model have been obtained. First, the conceptual model should be considered as it impacts all aspects of the study. Once the simulation has been constructed, one should properly handle the initialization bias and gather sufficient data to ensure that accurate results are received. Therefore, the warm-up period, run length and number of replications have to be determined. The final step of the simulation modeling is verification and validation. White-box and black-box validation are suitable methods according to the literature.

3 Current System Analysis

Section 3 aims to analyze the current system of this study to create a thorough understanding of the problem. Regarding the TOC, z section identifies and exploits the constraining machine corresponding to the second and third phases, respectively. As this section contains a relatively large amount of information, the section has been divided into two main sub-sections: Section 3.1 Field of Research and Section 3.2 Data Analysis. The field of research delineates the current system to understand the design, monitoring and control of the packaging line. The data analysis focusses on the current performance and bottleneck of the system including a conclusion.

3.1 Field of Research: Packaging line 41

As explained in Section 1.3, this case study focuses on the packaging process of the 5-liter keg line 41. According to Heineken (2017), a packaging line is defined as a series system of distinct machines working together in a sequence to fill beverage containers. Packaging line 41 produces a large product-mix of beers and ciders including Heineken®, Desperados, Affligem and Strongbow. Figure 3.1 shows a schematic overview of this production process. From the legend it is visible that this assembly process has been divided into three departments; namely, the wet, dry and palletization area. In Section 1.4, it has been described that the scope excludes the wet area and only contains the internal processes.

3.1.1 Total List of Machinery at Packaging Line 41

One or more (parallel) machines are used for each stage in this kegging line. The machines are put in a sequence and connected by conveyors, which function by design as buffers. In Figure 3.1, the process numbers correspond to these machines, which are briefly described in their process order below. Section 2.2 indicates that the most crucial machines for this research are the *filler (and clincher), (tray) packer, palletizer* and *shrink wrapper*. Therefore, Section 2.1.2 explains their core functions in more detail.

1. Depalletizer: Unstacks the draught kegs from the pallet, layer by layer, and drops them on a conveyor.
2. Decapper: Removes the cap from the keg and checks the status of the carbonator by inserting a needle inside the keg.
3. **Filler (and Clincher):** Fills the keg with beer and attaches a beer line (including cap) to it.
4. Rotator: Rotates the draught keg (upside-down) for the workstations upstream the process.
5. Activator: Activates the CO2-carbonator inside the keg by pressurizing it.
6. Rotator: Rotates the keg (right-side-up).
7. Warm Water Bath: Warms the keg to room temperature to prevent condensation of the package later in the process.
8. Drying Tunnel: Dries the outside of the keg to prevent condensation.
9. Top Chime Destacker: Unstacks the plastic top chimes (including taps) from a pallet and drops them onto a conveyor belt, which will transport them to the Top Chime Applicator.
10. Top Chime Applicator: Attaches the plastic top chime to the draught keg.
11. **(Tray) Packer:** Packs the kegs in pairs in a cardboard box.
12. **Palletizer:** Stacks boxes of kegs on a pallet.
13. **(Pallet) Shrink Wrapper:** Packs the pallet by using a shrink sleeve and sends it to the CS&L department.

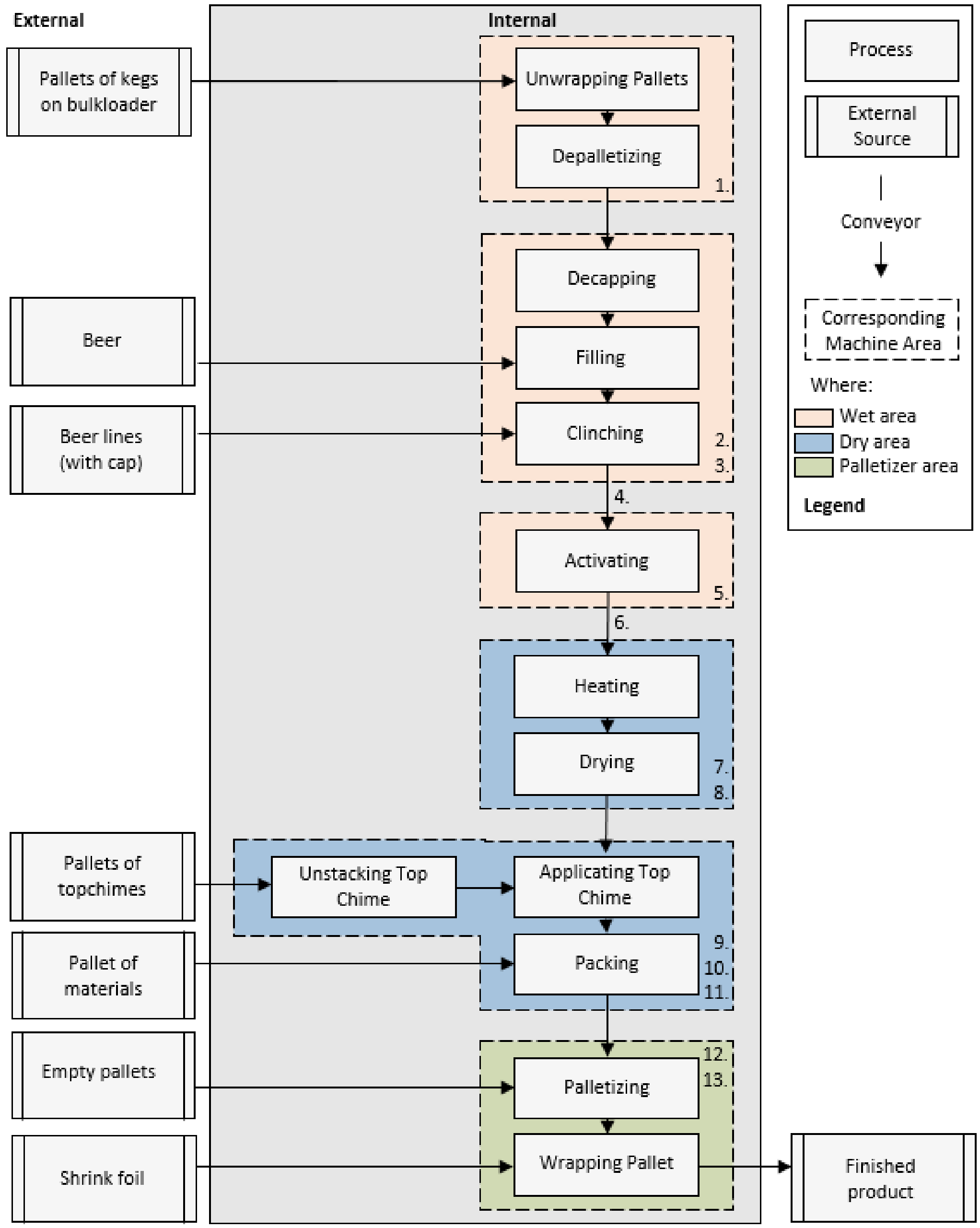


Fig. 3.1: Schematic overview of packaging line 41.

3.1.2 Deep Dive into Machinery Within Scope at Packaging Line 41

This section visualizes and describes the core functions of the most relevant work stations for this research in more detail.

Filler/Clincher (number 3. in Figure 3.1)

This production line contains four filling machines, which can all process seven kegs at the same times (see Figure 3.2). The beer is poured inside the keg through a 'beer line', as visualized in Figure 3.3 (number 1.). After the filling process, the draught kegs are transferred to the clinger. Finally, this machine attaches the cap, including tap line, to the keg.

Fig. 3.2: The Filler.

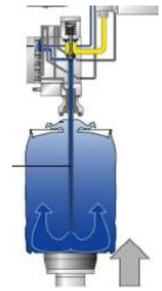


Fig. 3.3: Schematic Representation inside the filler.

Packer (number 11. in Figure 3.1)

When the 5L kegs arrive at the packaging process, the conveyor is split and kegs positioned as shown in Figure 3.4. Thereafter, the kegs are packed per duo by folding a cardboard box around it (Figure 3.5). These boxes can be partially open (see Figure 3.6) or closed. Lastly, a date and unique product code is lasered on the package.

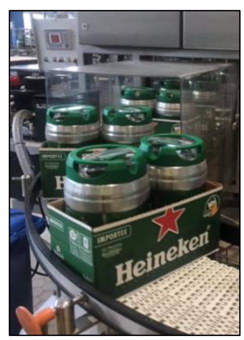


Fig. 3.4, 3.5 and 3.6: Representing the entry, folding process and exit of the packer, respectively.

Palletizer (number 12. in Figure 3.1)

The pairs of draught kegs arrive at the palletizer by conveyor once they are packed at the packer. Here, they are stacked on a pallet by this machine (see Figure 3.7). The *sheet applicator* (see Figure 3.8; (number 1.)) adds sheets between the layers to ensure a more stable pallet of 'open boxes'. On the other hand, these sheets are not used for a pile of 'closed boxes' as a small amount of non-slip liquid is sufficient. In addition, the stacking pattern varies per pallet and order. The most used pallet types (stacking patterns) are One-Way (i.e., 5x15 kegs and 6x15 kegs) and LPR (i.e., 5x12 kegs).

Fig. 3.7: Palletizer.

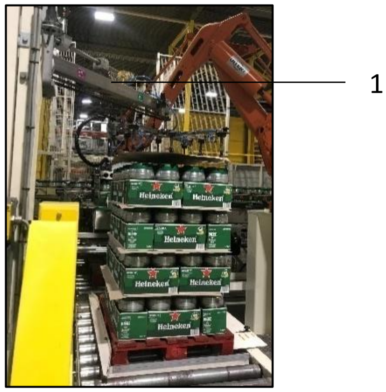


Fig. 3.8: Palletizer and sheet applicator.

Pallet Shrink Wrapper (number 13. in Figure 3.1)

The pallet shrink wrapper (see Figure 3.9), or shrink wrapper in short, is the final machine to be included in this research study. Finished pallets, of the three production lines (viz., line 41, 42 and 43), are transferred by an AGV (*Automated Guided Vehicle*) to this workstation. Figure 3.10 presents a schematic overview of this pickup process. The transport takes place between the palletizer output-buffers and input-buffer of the shrink wrapper. Once a pallet is carried to the shrink wrapper, it is packed by using a shrink sleeve. The foil shrinks due to a heat beam produced by this machine. Afterward, the pallet is stickered and retrieved by the CS&L department.

Fig. 3.9: Shrink wrapper.

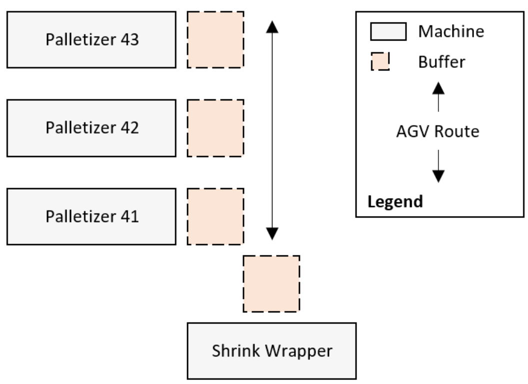


Fig. 3.10: Schematic overview of the AGV retrieval route.

3.1.3 Defining Machine Status at Packaging Line 41

In order to calculate line performance, it is necessary to understand the possible machine status; which indicates the machine conditions. These states are formulated below and explained using the schematic overview in Figure 3.11. In this figure $\mathbf{m_i}$ and $\mathbf{b_i}$ indicate a machine i and buffer b, respectively.

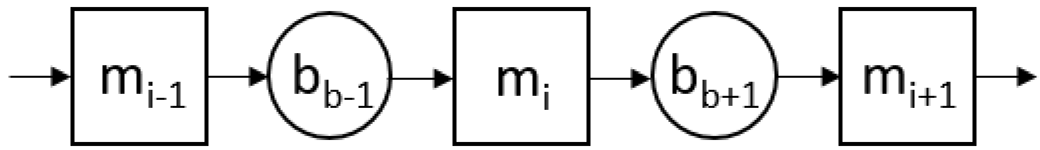


Fig. 3.11: Machine flow line.

Planned production stop: Machine m_i is in ***planned production stop***, when m_i is not producing parts due to a planned production stop. This can have several reasons including no orders, maintenance, unmanned time, cleaning.

Producing: Machine m_i is ***producing***, when m_i is producing products.

Blockage: Machine m_i is said to be ***blocked*** during a time slot, when buffer b_{b+1} is full at the beginning of a timeslot, and m_{i+1} fails to take a product from b_{b+1} at the start of the timeslot t (Dallery & Gershwin, 1992). There is no space at discharge of the machine, which is usually caused by failures of succeeding machines.

Starvation: Machine m_i is said to be ***starved*** during a time slot, when buffer b_{b-1} is empty at the beginning of a timeslot t (Dallery & Gershwin, 1992). There is a lack of infeed at the machine, which is mostly caused by failures of preceding installations.

Failure: Machine m_i is in ***failure***, when m_i is not able to produce products due to internal or external failure in a timeslot t. There is a difference between internal and external disturbances, depending on the origin of the failure (Saad & Gindy, 1998). As internal failures are caused by internal causes, such as the machine itself or human role, and external failures arise from external influences, such as logistics and material quality.

Unknown: Machine m_i has the status ***unknown***, when it is not able to produce products for unknown reasons. This state will be ignored during this research as the cause of this production stop is unknown.

A machine is either producing or not producing for one of these six factors. Blockages, starvations, status unknown, and failures are indicators of the losses made in the assembly process.

3.1.4 Human Role at Packaging Line 41

In this section, the direct influences of human working on this production line are described. The role of the operators and team leaders technical service is briefly discussed here as they are the direct internal stakeholders in this research.

The operators are the direct workforce at the production line. They are active on the work floor and operate the machinery on a daily basis. When an irregularity on the line occurs, they are the first responsible. Other core responsibilities include the batch changeover processes, quality checks and data registrations.

The team leaders can be described as the direct supervisors on the production line. They manage the operators and focus on the overall line performance in collaboration with the management. Unlike the operators, their work is indirectly related to the production process and includes long term processes.

3.1.5 Speed Regulation at Packaging Line 41

From the depalletizer to the palletizer, all machines are connected by conveyor belts. Lines are installed to transport kegs to the next machine downstream of the packaging process. These conveyors also function as a buffer between the machines. Heineken has determined the buffers' capacities based on the length and speed of the line by applying the *drum-buffer-rope* (DBR) principle. The DBR is a tool that is used in the TOC methodology and is a technique that helps to decide where in a process control should occur (Slack et al., 2010). A buffer is provided in order to decouple machines and cope with unexpected failures, which may disrupt the production process (Dallery & Gershwin, 1992). The machine upstream can produce until the buffer upstream fills up, and the machine downstream can operate until the buffer downstream becomes empty. The longer the buffer, the longer it will take before a buffer becomes full or empty.

Keg transportation is regulated by the sensors attached to the conveyor belt. A sensor tracks the presence and distribution of beverage containers on the line. As soon as it registers an irregularity the corresponding conveyor or machine stops, and restarts when the situation is normal. There are two types of sensors: switches and photocells. A switch must be triggered physically by a keg to become active, while a photocell beams a laser that must be interrupted.

3.1.6 Data Registration System: MES

In order to properly analyze the current state of the operational performance, data is required. This data is mainly collected via Heineken's data registration system MES (*Manufacturing Execution System*). This information system has been connected to all sensors and control systems on the production line. Operators can make marks and changes manually in the data system. The system consists of a database with relevant production data and shows all relevant real-time data. A print screen of the machine status during an eight hours production shift can be found in Figure 3.12.

Fig. 3.12: Screenshot of MES - Machine Overview

3.1.7 Calculations of Line Performance

At Heineken, the line performance is indicated by the OPI. It is similar to the OEE which has been described in Section 2.1. Therefore, this performance indicator is also a product of the availability, performance and quality, which is shown in its equations below. This section aims to explain the criteria that are relevant for the OPI equation construction. Its construction is visualized in Appendix 1. Appendix 2 provides an example calculation in order to get deeper insights of the equations.

$$\textbf{\textit{OPI = Availability}} * \textbf{\textit{Performance}} * \textbf{\textit{Quality}}$$

The performance can be calculated by dividing the production time by the operating time. The *production time* is the sum of the theoretical production time (good products) and rejected & reworked products, and rework time. By adding the speed losses and minor stops, the *operating time* can be calculated.

$$\textbf{\textit{Performance}} = \frac{\textit{Production Time}}{\textit{Operating Time}}$$

In order to calculate the Availability, the operating time and *manned time* are required. The manned time is calculated by subtracting the unused time from the total time.

$$\textbf{\textit{Availability}} = \frac{\textit{Operating Time}}{\textit{Manned Time}}$$

Finally, the quality is the fraction of the time required to create a “good product” divided by the time needed to create the real output (good product + reject & rework time). This thesis will not focus on improving the quality of the products.

$$\textbf{Quality} = \frac{\textit{Good Product}}{\textit{Good Product + Reject \& Rework}}$$

However, when the line performance is assessed, The *Operation Performance Indicator No Order No Activity indicated* (OPI NONA) is used. This can be explained due to the fact that a period without orders otherwise negatively effects the line performance. In addition, non-team maintenance is not included either. The OPI is based on the efficiency of the core machine, which is the filler in this study.

3.2 Data Analysis

This data analysis explains the tools used to measure the current performance and bottlenecks of the system. Based on the results, the main bottleneck will be analyzed in more detail which will lead to potential solutions.

3.2.1 Bottleneck Detection by Data Analysis

The first step of the TOC is to identify the system's constraints because these are the weakest links of the manufacturing process (see Section 2.2). Since the filling process is the core activity in this assembly line and the line efficiency is determined based on its performance, an indication of the bottleneck location has been obtained by analyzing the filler's data. By observing the states of the losses, as presented in Figure 3.13, it is clear that most of them are caused by blockages and therefore downstream the packaging process.

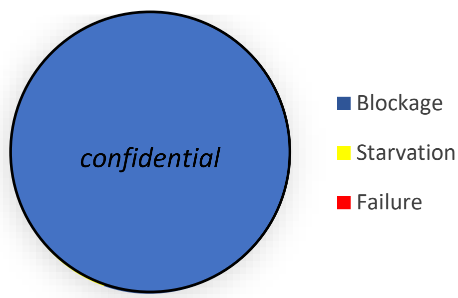


Fig. 3.13: Machine state pie chart of the filler.

As the direction of the bottleneck in the system has now been identified, findings in the literature have been examined for further bottleneck detection. In Section 2.3 of the literature study, the following two bottleneck methodologies are introduced: the *turning-point methodology* and v-graph methodology.

Turning-Point Methodology

The turning-point method (see Section 2.3) is a data-driven identification technique based on the machine states in a system. The principle is simple, if the blockage time of the upstream machine is higher than the starvation time of the subsequent machine, the bottleneck must be downstream; otherwise, the bottleneck is located upstream. This "arrow-based" approach has been applied in this study because all required data is available in Heineken's MES. Moreover, the method clearly delineates the critical point in the system as presented in Figure 3.14, and emphasized in Figure 3.15 where the turning point has been illustrated.

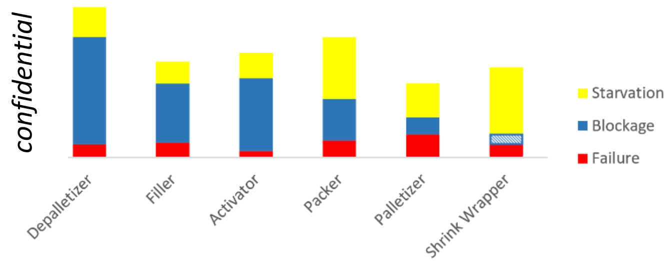


Fig. 3.14: Machine state overview of packaging line 41.[5]

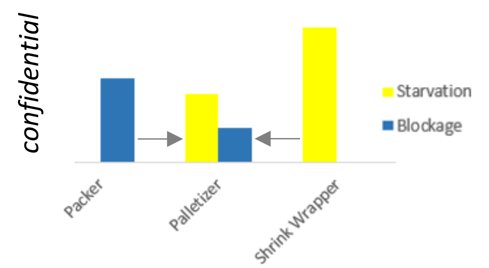


Fig. 3.15: Arrow-based bottleneck detection.

In Figure 3.14, it is visible the blockage of upstream machines is higher than the starvation of the subsequent within the segment from the depalletizer to the palletizer. Then, blockage becomes higher than starvation (from the palletizer to the shrink wrapper, respectively) which is shown in Figure 3.15. Therefore, the palletizer must be the turning point and constraining machine in this system according to this technique.

V-Graph Methodology

The v-graph theory (see Section 2.3) is a buffer strategy that has been adopted by Heineken to optimize line performance. By implementing the v-graph in packaging line 41, overcapacity increases for machines that are located at a larger distance from the core machine (filler). In this way, accumulation can be restored after a breakdown has occurred. As the v-graph principle is the core philosophy in Heineken's line balancing, it is interesting to sketch the current situation according to this theory. Moreover, the MER is also relevant because the machine containing the lowest MER value (see also Section 2.3) usually is the bottleneck machine. These real-time machine speeds have been acquired in collaboration with the process automation department. These were not available at packaging lines 41 and 42 beforehand. The nominal machine capacities and corresponding MER values of packaging line 41 have been plotted in Figure 3.16.

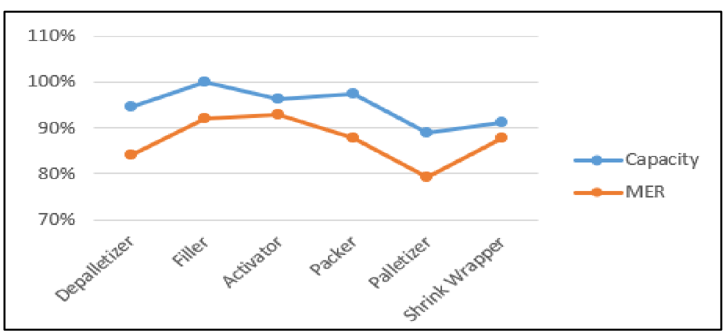


Fig. 3.16: V-graph of packaging line 41 including machine capacities, MER and line efficiency.

Despite the filler is the core machine in packaging line 41, it is not the constraining machine in the system. From the v-graph in Figure 3.16, it is visible that the palletizer is the weakest link based on its MER value as well. This machine behaves as the system's bottleneck for the largest fraction of the time. Whereas, the shrink wrapper is the constraining machine if all three packaging lines (see Section 3.1.2) are operating at full efficiency. This shifting bottleneck can be clarified because the shrink wrapper is the meeting point of

[5] Due to inaccurate data registration in MES, an estimate has been made of the shrink wrapper's blocking time (see Appendix 4).

three production lines and does not meet the required capacity standards for this situation. The calculations that proof this phenomenon are provided in Appendix 3. However, it is not sufficiently clear what percent of the time this scenario takes place. Likely less than 5% of the actual production time.

Taking both detection methods into consideration it clear the palletizer behaves like the system's bottleneck. The turning-point methodology indicates most losses are caused by the machine. By observing the v-graph and MER values of the system, it is visible the palletizer has the lowest capacity and behaves likes the bottleneck most of the time.

3.2.2 Bottleneck Analysis Through Data Observation

Now it is evident the palletizer is constraining machine in the system, a thorough analysis of this work station has been conducted. In Figure 3.17, a visualization of the palletizer standstill causes has been presented. It is clear that both failures and blockages have a large impact on the performance of the machine; X% and X% (*confidential*), respectively. Firstly, a failure analysis has been conducted to identify the root causes. Whereafter the flow from and towards the palletizer has been observed for potential points of improvement.

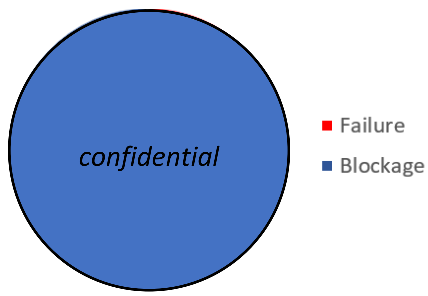


Fig. 3.17: Pie chart of palletizer standstill causes.

Pareto Analysis of the Palletizer Failures

As the identification phase has been finished, this section further covers the analyzation phase of this research, which is corresponding to the second stage of the TOC; to exploit the system's constraint. A Pareto analysis (see Section 2.3) has been carried out to identify the vital errors causing stoppages at the palletizer. Figure 3.18 presents the five most common failures. It is visible the sheet applicator failure is the most dominant error based on appearance and duration. On average 30% of all palletizer failures are sheet applicator "pickup failures". The failure is defined as a minor stop according to Heineken standards as the average duration is less than 5 minutes (viz., 230 seconds per failure on average in April 2019). This behavior is relevant for the further approach as minor stoppage losses occur when the production is interrupted by a temporary malfunction (Afefy, 2013).

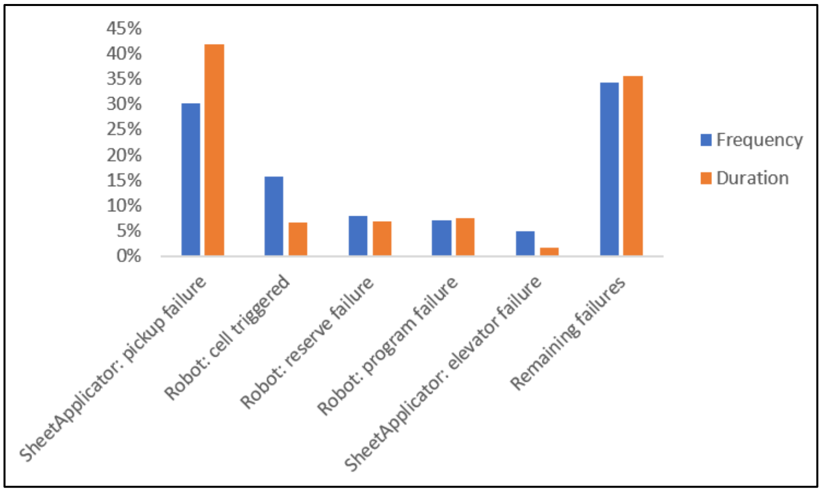


Fig. 3.18: Pareto diagram of the palletizer failures.

Ishikawa Diagram of the Sheet Applicator Failure

From the Pareto analysis it is clear, the sheet applicator failure is the most common error at the palletizer. In order to get a better understanding of the failure, it has been captured on camera (see Appendix 5). Meanwhile an Ishikawa diagram, or fishbone diagram, has been established to systematically find the root cause of this problem. The literature suggest including a data analysis to verify assumptions of this diagram (see Section 2.3). The diagram, including most relevant findings, is presented in Figure 3.19. In this section, the focus is on the following headings: environment, material and methods. The others are addressed in Section 6.1.

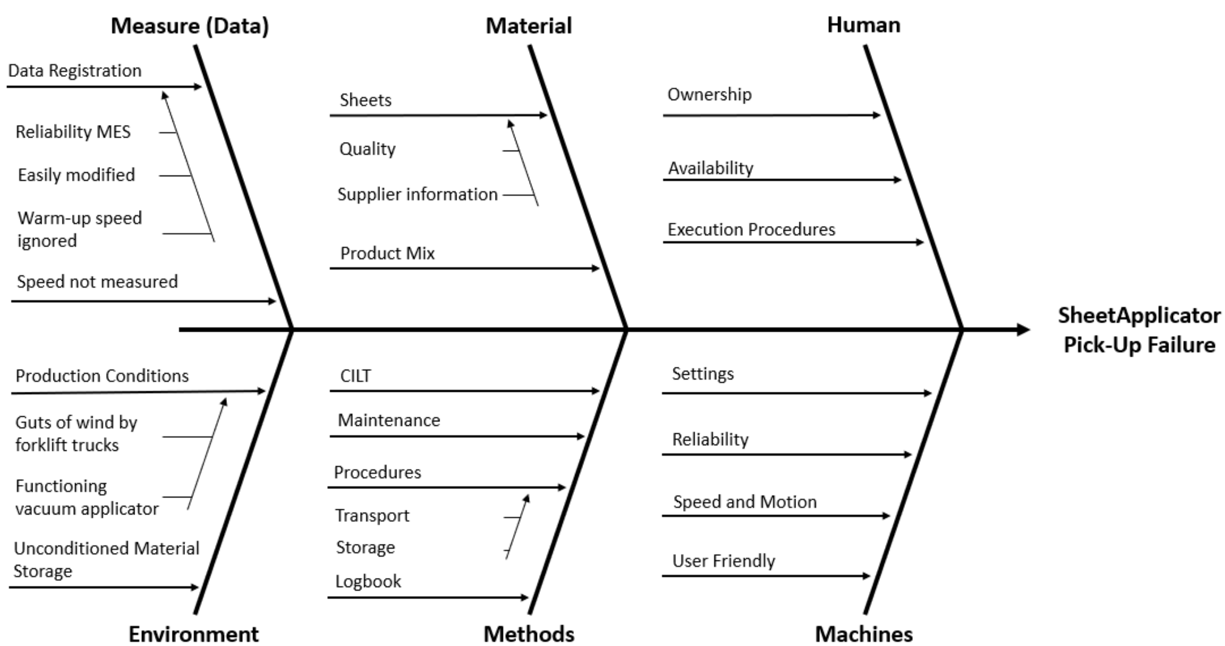


Fig. 3.19: Ishikawa diagram of the sheet applicator pickup failure; including the most relevant findings.

The key founding from the fishbone diagram was the fluctuating sheet quality. The widest varying were its structure (i.e., smooth vs. corrugated) and humidity (i.e., relative humidity of 25% to 50%). Pictures of the material have been included in Appendix 6.

Cause Analysis of the Sheet Applicator Failure
To prove whether there was a causal relationship between the occurrence of pickup failures and the quality of sheets, the failure have been simulated in real-life. Pictures of the poor material are added to appendix 6. Based on these similarities, good and poor material have been divided and used for production separately. Since the production process should not be drastically impeded by this experiment, the testing of three stacks of bad material was executed for an hour each. A screen print of its bad influence on the production process is presented in the red circles of Figure 3.20.

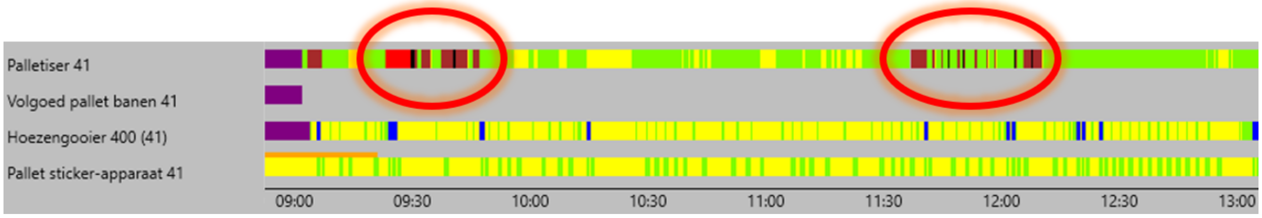


Fig. 3.20: Example data string of the poor material experiments.

As filtering on good material had no negative consequences, this test has been executed without limiting conditions. The data distributions of the process including unfiltered material has been compared to the results of the test including only good material. The distributions have been presented in Figure 3.21. From this figure, it is visible the failure is occurring less frequent when the material is properly selected (viz., increased average MTBF of 3692 seconds). The relationship between material quality and failures has been approved based on these tests.

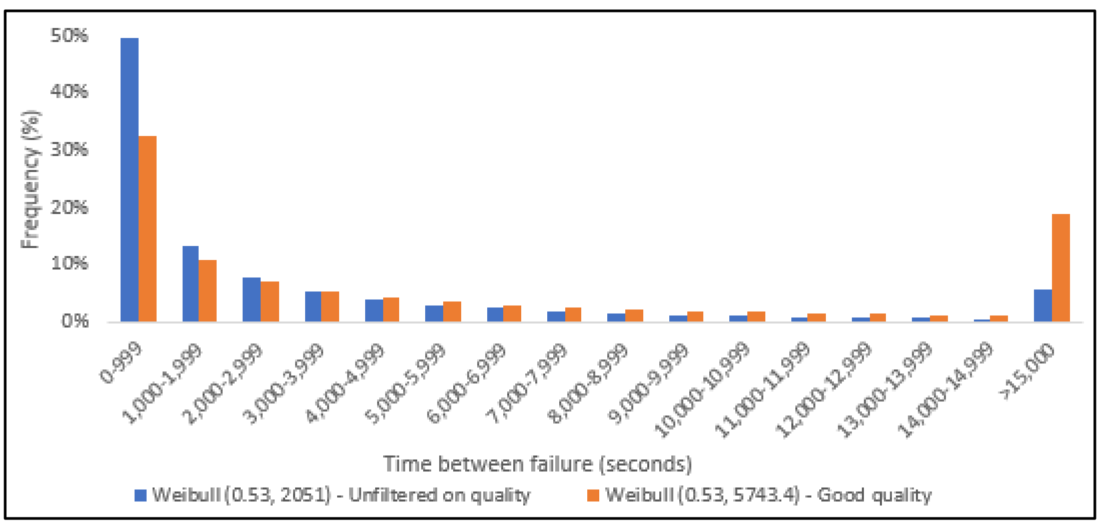


Fig. 3.21: Sheet Applicator – MTBF distribution comparison.

As the causal relationship has been determined, the next step was to detect its cause. The sheets arrive (packed in foil) per pallet in the warehouse. It consists of thin coated paper, which is prone to damage. Therefore, this study observed whether the established procedures have been carried out properly regarding the material. For instance, the pallets of material have to be packed in foil and stored conditionally. Moreover these should not be stacked as otherwise the material is likely to be damaged.

The material, however, is not stored in such ideal storage. To experiment the environmental effect, the material was stored in the least suitable unconditioned spot (i.e., the entrance of the warehouse) for two weeks. Testing the material did not show decreased performance. Moreover, its structure did not changed either.

It is relevant to observe the sheets upon arrival as its state does not deteriorate in the warehouse. A number of deliveries have been analyzed based on the state of the material (i.e., quality) and procedures. By monitoring these deliveries, it became clear the material already arrived with poor quality. Testing this material showed identical poor performance compared to the experiment including bad material.

Among the operators of the palletization department, there was a gut feeling of a causal relationship between the occurrence of pickup failures and the quality of sheets. The poor quality had long been known to the operators. However, the usual procedures to tackle the problem, were not thoroughly carried out (i.e., to create a blockade and/or "Leveranciers Klachten Systeem" [Supplier Complaint System]).[6] Instead, they learned to live with the frequently occurring breakdown.

Work Flow Analysis of Adjacent Machines

As the TOC states, a bottleneck must work at all time as lost production time on a bottleneck is irreversible. Therefore, the third step of this theory is to analyze the flow towards and from the palletizer to subordinate the non-constraints to the palletizer's needs. The research area is the work flow between the adjacent workstations. Hence, the flow from the packer towards the palletizer and palletizer towards the shrink wrapper.

The packages of draught kegs are moved to the palletizer by conveyor once they have been packed at the tray-packer. Before the parts arrive at the palletizer the parts are divided over two conveyors by a switch as shown in Figure 4.2. Section 4.1 explains the numbers and letters used in this figure. This is necessary since the palletizer stacking pattern requires two input-sources. This process have been analyzed by both empirical and data observation. From the empirical research it appeared minor starvations frequently arose at the palletizer. The root cause was the switch regulation. The switch pattern did not match the distribution of the palletizer's stacking pattern. This is visible from the distribution in Table 3.1. As a result, the left lane regularly becomes idle, which causes starvation at the palletizer. Meanwhile, the processes upstream were delayed which was also noticeable from the MES data. At the same time, blockages and starvations occurred at the packer and palletizer, respectively (see Figure 3.22).

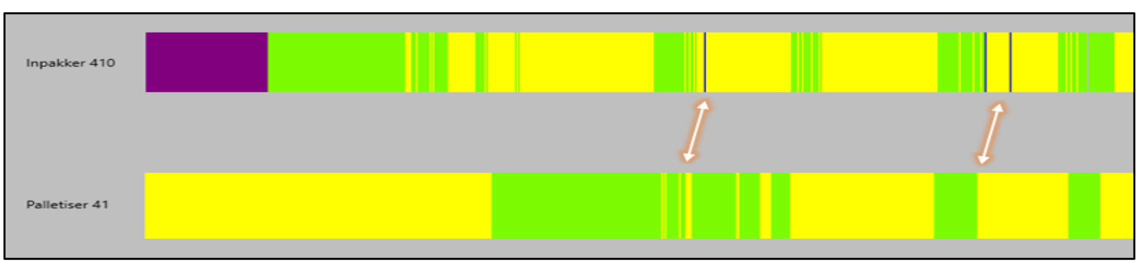


Fig. 3.22: Blockages on the packer without failures occurring at the palletizer.

[6] Leveranciers Klachten Systeem: A procedure that needs to be exploited to report poor material quality, caused by the supplier, to the quality department of the brewery.

Table 3.1: Comparison of the switch pattern and stacking pattern distributions.

Distribution	Left Lane	Right Lane
Switch Pattern	30%	70%
Palletizer Stacking Pattern	43%	57%

From observing the flow downstream the process, it is clear that also a large amount of palletizer standstills is caused by blockages (see Figure 3.15). The shrink wrapper is the meeting point of packaging line 41,42 and 43 as has been mentioned in Section 3.1.2. Finished pallets of the three assembly lines are transferred to this workstation by an AGV. This retrieval process is regulated according to a combination of the SPTF rule and FIFO rule (see Section 2.4). If the output buffer utilization of palletizer 43 is smaller than two, the SPTF rule is applied. Otherwise, the AGV gives priority according to the SPTF rule. This policy has been confirmed by the contractor (viz., Company X (*confidential*)) and has been empirically observed.[7]

As no buffer utilization data is stored in MES, it has been empirically experienced that buffer 43 has a lower utilization than the other lines. The potential cause is its larger buffer capacity (viz., 3 pallets vs. 1) in combination with the FIFO dispatching rule. Moreover, it has been explained the shrink wrapper is a critical area in the packaging lines (see Section 3.2.1). Blockages are caused when failures take place at this machine or if all lines are running at full performance. As a result, all line performances are obstructed. Because of these latter reasons, it is relevant to observe and optimize the current AGV priority assignments. By optimizing this flexible routing system, potential losses can be reduced.

3.2.3 Validation of the Data

Numerous data validation techniques have been conducted to ensure a reliable and sufficiently accurate research study. Every effort has been made to ensure that the data were as accurate as possible. The data has been mainly acquired by the information system MES, which stores a large amount of relevant line and process data. This data have to be imported to Excel in order to find patterns by data analysis methods, such as analyzing graphs and pivot tables.

The data has been validated by “going to Gemba” which means visiting the shop floor to understand the actual process (see Section 2.3). On the work floor, the process has been recorded by camera, tracked by stopwatch and empirical observed. Interviews have been conducted with specialists such as operators, technical services, suppliers and the maintenance department. Moreover, Heineken’s internal documents have been used, such as maintenance and operating manuals.

Furthermore, the data have been thoroughly observed on its source, patterns and modifications. Moreover, a tool for validating modified blockage ratios has been developed based on Heineken’s line balancing techniques. From which a detailed description is provided in Appendix 4.

[7] Van Uitert BV is a company mainly focusing on mechanical engineering of internal transport systems in the beverage and food industry.

3.2.4 Conclusion of the Data Analysis

Based on the data analyzation, it can be concluded that the palletizer is the most critical machine at packaging line 41. The largest improvement of the line performance can be obtained by focusing on and controlling this bottleneck. Based on the flow towards and from the palletizer, the final scope of this research has been determined. This starts at the packer and ends with the shrink wrapper as visualized in the schematic overview of Figure 3.23. In this figure, the most important points of improvement for the solution phase also have been provided: the switch regulation, sheet applicator failure and AGV dispatching rules.

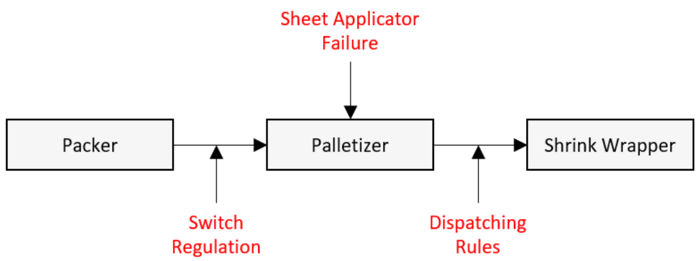


Fig. 3.23: Flow diagram of the scope including points of improvement.

4. Solution Design

The goal of the solution design is to elevate the system's constraints by creating a simulation model and experimenting with the current system. This corresponds to the fourth step of the TOC, which is to elevate the system's constraint. First, Section 4.1 explains how the conceptual model of the current system has been created. Once this model has been delineated, the corresponding simulation is presented in Section 4.2. In Section 4.3, potential solutions have been formulated based on the findings of section 3. Subsequently, the results of their experiment factors are presented in Section 4.4, after which Section 4.5 expresses the most relevant results in OPI. Finally, a summary of the solution design has been provided in Section 4.6.

4.1 Conceptual Model

The conceptual model is a non-software description of the simulation model that has been developed (see Section 2.5). That section states, the model has been created based on the following six key components: objectives, content, inputs, outputs, assumptions and simplifications. Figure 4.1 presents the components selected for this model. Therefore, these have been described with regard to this simulation study.

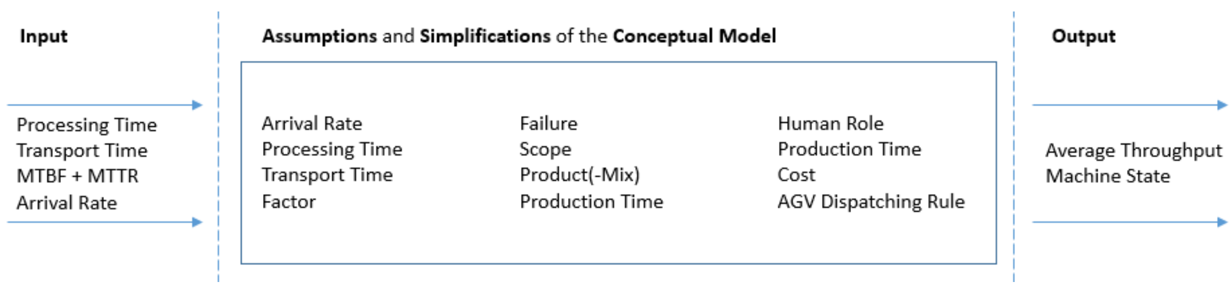


Fig. 4.1: Overview of the key components in the model.

4.1.1 Objective of the Conceptual Model

The purpose of this study is to improve the OPI by increasing throughput. Relevant points for improvement have been identified in Section 3.2, namely the switch regulation, sheet applicator failure and AGV dispatching rules. Therefore, this simulation model has been designed with the goal of proving whether alternative solutions improve line performance regarding these findings.

4.1.2 Content of the Conceptual Model

The model aims to increase throughput by experiments with regard to the findings in Section 3.2. Therefore, the scope should consider all relevant factors and responses involved. Although line performance is measured at the filler in real-life, this station has not been included in the model. The layout of this model has been designed as presented in Figure 4.2 due to inaccessible data and strongly correlated processes. The numbers and letters used in this figure are explained later in this section. The input-buffer of the packer behaves as the entrance of line 41 and shrink wrapper as the general exit point of the model. In addition, the workstations of lines 42 and 43 have been excluded from the model because the required data were not available and time management played a role in this study.

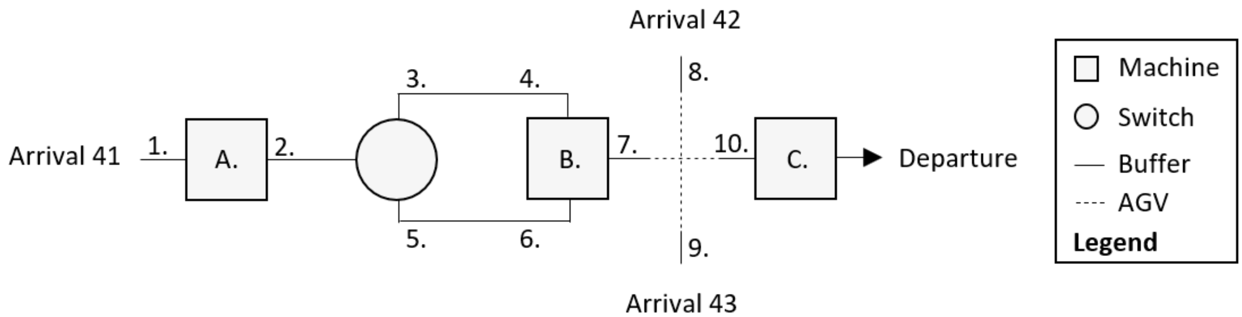


Fig. 4.2: Layout of the conceptual model's packaging line.

Robinson (2004) considers the 80/20 rule as an appropriate tool to determine the level of detail. For that reason, the model has been designed on machinery level as it is mainly focused on improving flow and reducing failures. Moreover, the most critical processes have been included to accurately predict throughput.

4.1.3 Inputs of the Conceptual Model

Different types of input data are required for this discrete event simulation. All data has been validated according to the techniques described in Section 3.2. This section describes what input data is required and how it can be modeled. When considering this input data, the experimental factors are not taken into account because they are not predetermined input data and can be specified by the user. These experimental factors are: the product arrival rates, dispatching rules, switch regulation and varying sheet applicator failure distributions and speed of the shrink wrapper.

In this conceptual model, there are four important types of input data which have been defined as:

1. processing times,
2. transport times,
3. *mean time between failures* (MTBF),[8]
4. *mean time to repair* (MTTR),
5. arrival rates

(1) Processing Times

Table 4.1 presents the processing times per package of the machines in this model. In this table, a letter is linked per machine (viz. A, B and C), which corresponds to the letters used in Figure 4.2. As little information of these processing times was available beforehand, the real-life data has been measured in collaboration with the Pa-/Pi engineering (or process automation) department. A deterministic processing time has been selected for the packer and palletizer as their speed was constant while processing. Figure 4.3 provides a visualization of the packer's real-time data. On the other hand, the shrink wrapper's speed was clearly varying over time. Therefore, a uniform distribution (standard deviation of 0.33 seconds) has been chosen to cover this fluctuation as no data distribution was fitting this relatively small selection of data.

---

[8] The MTBF is interpreted as the total producing time of a machine between the end of one breakdown to the start of the next.

Table 4.1: Machine processing times input data (confidential).

Machine	Machine	Processing time (s)
A.	Packer	
B.	Palletizer	
C.	Shrink Wrapper	

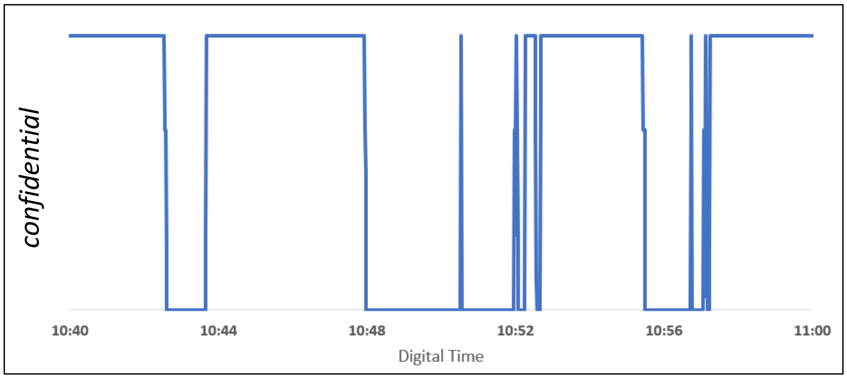


Fig. 4.3: Visualization of the processing time at packer.

(2) Transport Times

In this conceptual model, the parts are transported between machines by ten buffers and one AGV. Table 4.2 describes the transport times and capacities of these buffers. These buffers are labeled as numbers (viz., 1 to 10), which are corresponding to the labels used in Figure 4.2.

Table 4.2: Transport times and capacities of the buffer input data.

Buffer	Transport time (s)	Capacity	Buffer	Transport time (s)	Capacity
1	60	54	6	0	6
2	200	100	7	8	1
3	30	14	8	8	1
4	0	4	9	25	3
5	35	18	10	2	25

Considering the buffers as constructed in this model, there are two relevant remarks. First, buffer 2 is the only accumulating buffer and contains the accumulation of buffers 2 to 6 – which is 50 seconds. Figure 4.4 presents a flow diagram of this process. Secondly, buffers 4 and 6 do not contain a transport time as these serve as buffer exit. The packages leave this exit according to the palletizer stacking pattern. Appendix 7 includes a flow chart describing this pattern as developed in the conceptual model. Therefore, their transport times have been included in buffers 3 and 5, respectively.

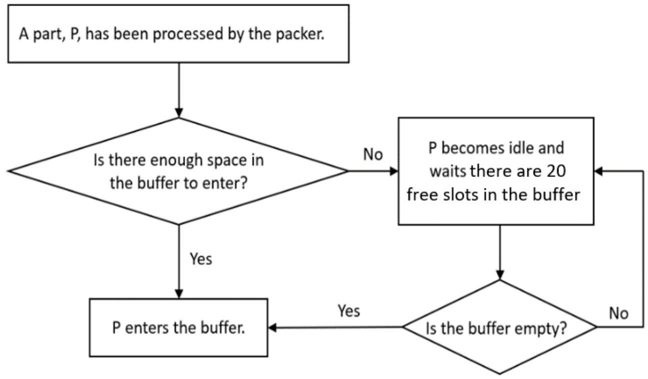


Fig. 4.4: Flow diagram of the accumulation procedure.

The AGV can carry at most 1 part per time, and travels and (un)loads with a deterministic transport time as the variation in its duration was really small. Table 4.3 shows the transport times. These times depend on the AGV's current load (i.e., nothing or one pallet) and distance to travel.

Table 4.3: AGV transport times input data.

From\To	**Shrink wrapper**	To\From	**Shrink wrapper**
Buffer 7	9.7 seconds	Buffer 7	9.7 seconds
Buffer 8	37.8 seconds	Buffer 8	27.7 seconds
Buffer 9	47.9 seconds	Buffer 9	33.6 seconds

(3) Mean Time Between Failures and (4) Mean Time To Repair

The data has been modeled as statistical distributions to create more randomness in this simulation study. Robinson (2004) states, a sensitivity analysis can be performed more easily as only the distributions parameters need to be altered. Therefore, the statistical distribution should give the full range of variability that might occur in practice. The appropriate distribution is selected by considering the properties of the failure and fitting the empirical data. For the latter technique, the program Minitab has been used combined with a Chi-squared test (see Section 2.5) in Excel. Figures of the distribution fitting have been provided in appendix 8. Table 4.4 summarizes these results. An exponential distribution has been given to the shrink wrapper as the MTBF was not available due to inaccurate data registration (see Appendix 4). This distribution and corresponding value have been determined by treating the data as an experimental factor until the desired result is achieved, which is an appropriate method according to Robinson (2004).

Table 4.4: Machine failure input data.

Machine	**MTBF (minutes)**		**MTBF distribution**	**MTTR (minutes)**		**MTTR distribution**
	α	β		μ	σ	
Packer	0.33	278.4	Weibull	57.3	250.4	Lognormal
Palletizer	0.43	863.9	Weibull	153.7	276.3	Lognormal
Sheet Applicator	0.53	2051	Weibull	165.8	185.9	Lognormal
Shrink Wrapper	-	3154	Exponential	209.3	307.2	Lognormal

(5) Arrival Rates

The arrival rate has been selected based on the DBR principle, which states that the line's capacity is equal to the machine with the highest processing time. As the bottleneck of line 41 has been implemented in the model, the filler acts as the drum for the upstream processes. Identical to the selection of failure distributions, the most appropriate distribution for the arrival rate behavior has been chosen. A summarization of this data is collected in Table 4.5. As little data is available of packaging line 43, the exponential distribution has been selected for the *Mean Time Between Starvation* (MTBS) and Erlang for the *Mean Time Of Starvation* (MTOS). An empirical distribution (histogram) has been picked for the MTBS of packaging lines 41 and 42 as no statistical distribution was applicable. Identical to the MTBF of the shrink wrapper, the variables of the data unavailable have been selected by treating the data as an experimental factor as well.

Table 4.5: Arrival rate input data (confidential).

Line	Arrival rate (hour)	Mean Time Between Starvation	Mean Time Of Starvation
41	X kegs	Exponential	Erlang
42	X pallets	Empirical	Lognormal
43	X pallets	Empirical	Lognormal

4.1.4 Outputs of the Conceptual Model

In this conceptual model to two core KPIs are used to measure line performance:

(1) Average throughput – This is the core KPI and expresses the average amount of kegs per hour leaving the system.
(2) Machine states – The machine states present the fraction of time a machine is in a certain state. These are determined to obtain deeper insights into a modification's direct effects.

4.1.5 Simplifications and Assumptions of the Conceptual Model

Finally, assumptions and simplifications have been made in this model.

Simplifications

1. The scope of the model includes the packer input-buffer to the shrink wrapper (see Section 4.1.2);
2. No transport times at buffers 4 and 6 (see Section 4.1.3);
3. Buffer 2 serves as the accumulating buffer for buffers 2, 3, 4, 5 and 6 (see Section 4.1.3);
4. All parts entering and leaving the system are good products – data indicates this scenario takes place more than 99% of the time in real-life;
5. Pallet product-mix for line 41 and 42 is 5 layers including 12 packages each – this is the most critical and common product-mix (viz., 62% of the time);
6. Pallet product-mix for line 43 is 49 products per pallet – this is the most common product-mix (viz., 45% of the time);
7. External factors are not included – this slightly affects the machine ratios (e.g., blockages caused by CS&L pickup times);
8. The operator is excluded – its influence is already included in the failure distributions;
9. The model simulates the "actual production time" (see Appendix 1) – this model aims to simulate the steady-state behavior of processes;

10. Failures longer than 30 minutes are excluded – these failures are incidental and affect the steady-state behavior of processes;
11. Breakdowns do not occur at the buffer lines and AGV – these breakdowns are negligible in real-life;
12. Costs are not included in the simulation – tradeoffs (regarding costs) are provided in Section 5

Assumptions
1. Stochastic arrival rates for the products (see Section 4.1.3);
2. All production and transport times are fixed (see Section 4.1.3);
3. The AGV and all machines in the system are single-load stations (see Section 4.1.3);
4. Failure behavior has been modeled according to the data distributions;
5. The palletizer and sheet applicator failures are two different failures, which cannot occur simultaneously – the model aims to simulate the effect of the sheet applicator failure;
6. The model aims to simulate the effect of the sheet applicator failure,
7. The AGV pickup priority is determined based on the SPTF and FIFO dispatching rules (see Section 3.2).

4.2 Simulation Model
The conceptual model has been implemented in a discrete-event simulation model. A discrete-event simulation mimics the operations of a real system as a discrete sequence of state changes in time. The simulation has been designed in Siemen's program "Technomatix Plant Simulation". This is a simulation tool to create digital models of logistical problems systems, in order to examine the system characteristics and optimize performance (Siemens, 2012).

The main layer of the simulation model has been presented below (see Figure 4.4). This layer represents the palletization area, where the AGV pickup and delivery process takes place. Moreover, this layer consists of two frames – (1) "Line 41" (see Figure 4.5) which mimics the behavior of packaging lines 41 and (2) "Output" where all relevant output data is stored.

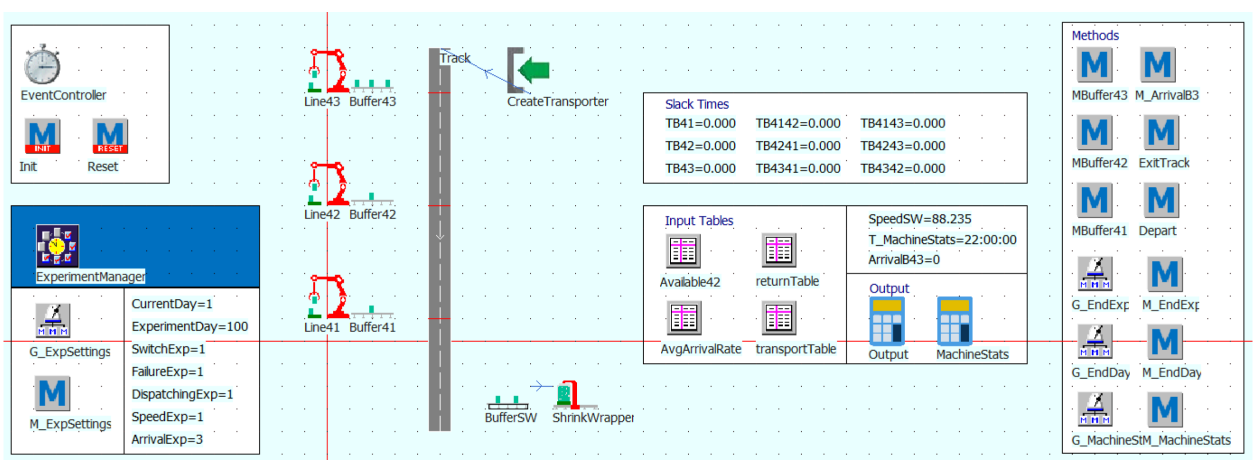


Fig. 4.5: Main layer of the simulation model.

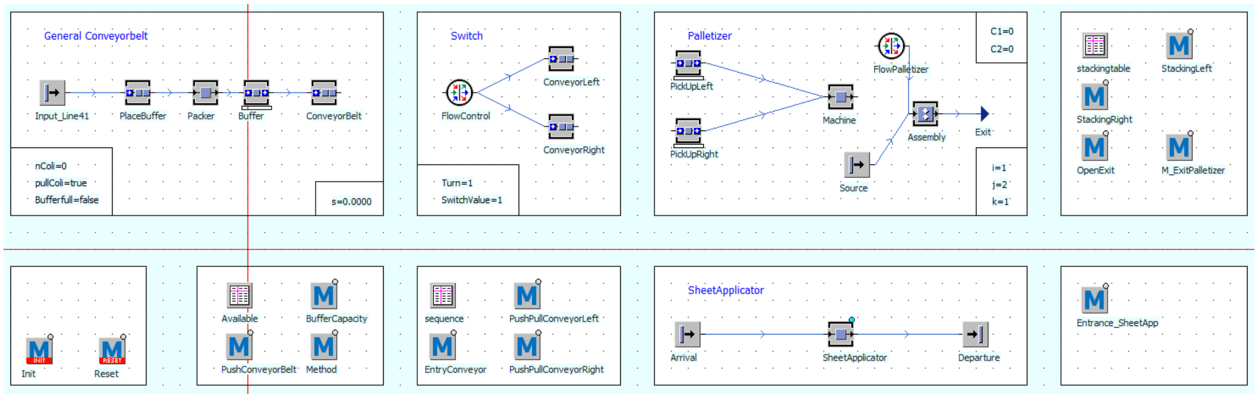


Fig. 4.5: Simulation model of the layer representing packaging line 41.

4.2.1 Experimental Setup of the Simulation Model

It is important that the experimentation of the simulation model is carried out correctly as it aims to get a better understanding of the real-world system. First, the choice of the nature of the model has been explained because it affects the means in which accurate results are obtained (see Section 2.5). Thereafter, the initialization bias and procedure of obtaining sufficient data are considered for the identical reason.

Nature of the Model

As mentioned in Section 4.1, the model strives to increase throughput by simulating the steady-state behavior of processes. The demand is infinite and the model never empty. Thus, it has been decided that this model is designed as non-terminating (see Section 2.5). Moreover, the simulation input and output data have been identified. In this simulation, the output is varying according to some fixed distribution and, therefore, identified as steady-state output (see Figure 4.6).

Warm-Up Period of the Model

In this simulation study, the initialization bias has been tackled by collecting data after the system warm-up period. This initialization period has been determined by the Marginal Standard Error Rule, which is introduced in Section 2.5. The rule has been applied to the mean throughput rate a day (per line) as it is the main KPI in this simulation. The *Marginal Standard Error Rule* (MSER) values have been determined manually. Thereafter, the warm-up period has been calculated by the corresponding tool in Excel. As the effect of the initialization bias is relatively small, it is not visible by plotting this average throughput rate (see Figure 4.4). The outcome is a warm-up period of one day (simulation time), which can be clarified as the real-life system also reaches its steady-state relatively fast. Moreover, the size of the system has been reduced in the model due to simplifications.

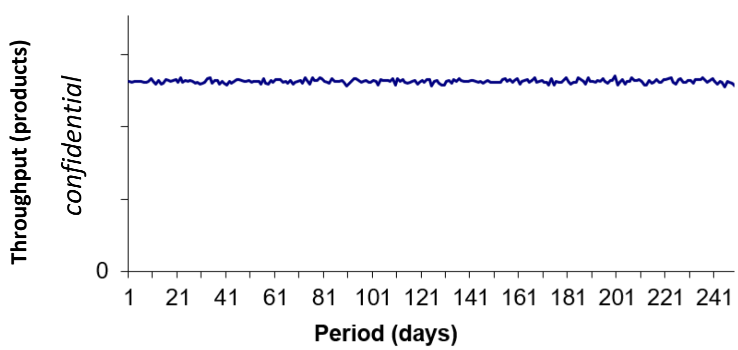


Fig. 4.6: Average throughput rate of the total simulation system .

Rung length of the Model
There is no natural endpoint in the model because it is non-terminating. According to the rule of thumb, the run length of the simulation should be at least 10 times greater than the warm-up period (see section 2.5). To be certain, a run length of 20 days has been selected because the warm-up period is relatively short (viz., one day).

Number of Replications Performed
Multiple replications are performed in this simulation because it obtains a better estimate of the mean performance compared to the single long run (see Section 2.5). The applied number of replications have been determined by using the confidence interval method as introduced in Section 2.5. Here, a confidence interval of 95% has been used. Table 4.6 shows the computation of the number of replications. Here the statistical test shows three replications are sufficient. This meets the standards of the rule of thumb, which states at least three to five replications should be executed (see Section 2.5).

Table 4.6: Number of replications.

Replication	Throughput	Average	Variance	T-value	Relative error	Confidence interval
1			-	-	-	-
2				12.70	0.10	90%
3				*4.30*	*0.04*	*96%*
4				3.18	0.03	97%
5				2.78	0.02	98%
6				2.57	0.02	98%
7				2.45	0.02	98%
8				2.36	0.01	99%

4.2.2 Input Sensitivity Analysis

In this simulation, a sensitivity analysis has been conducted on the estimated variables of the current system to analyze its behavior in terms of machine states and bottleneck behavior. Therefore, this sensitivity analysis examines the arrival rates of line 41 and the MTBF of the sheet applicator. This sub-section introduces the criteria, while Section 4.2.3 presents the results of this analysis.

First, the arrival rate of line 41 has been assessed to test the effect of its empirical distribution on the current system's performance. Therefore, the current scenario (*scenario C1*), has been compared to an arrival process without errors (*scenario C2*) to assess the influence of the losses caused by the system. Therefore, the interval of arrival remains the same. Moreover, the system's behavior is tested in a situation without an interval of arrival (*scenario 3*) to test the system's maximum throughput. Table 4.7 summarizes the criteria corresponding to these three scenarios.

Table 4.7: Sensitivity analysis of arrival rates (line 41).

Scenario	Interval of Arrival	Distribution	Demand
C1	X (*confidential*)	Empirical and Statistical	Infinite
C2	X (*confidential*)	Deterministic (constant)	Infinite
C3	0 seconds (constant)	Deterministic (constant)	Infinite

Secondly, the sensitivity analysis examines the effect of the shrink wrapper's MTBF as programmed in the model. As described in Section 4.1, the current value has been determined by treating the MTBF as an experimental factor. Hence, its influence on the system's behavior has been analyzed by comparing two additional experiments to the current system (scenario C1). *Scenario 4* concerns a decreased MTBF of -10%, while the system has been assessed by increasing this value by +10%. Table 4.8 presents the MTBFs associated with these scenarios.

Table 4.8: *Sensitivity analysis of MTBF (shrink wrapper).*

Scenario	MTBF of Shrink Wrapper
C1	52:33.73 min
C4	47:18.36 min
C5	57:49.10 min

4.2.3 Results of the Current System Simulation

The purpose of this study is to improve the throughput rate of packaging line 41. To determine progression, it is important to have a benchmark of the current performance. This section shows the output data of the main KPIs used for the current model. Moreover, this sub-section includes the results of the sensitivity analysis (i.e., *scenario C2* to *scenario C5*).

Table 4.9 presents the output data describing the system's throughput rate. In this table, scenarios 2 and 3 are presented in the same row as these experiments provide the same output data. Their throughput rate of line 41 is significantly higher compared to the current situation. On the other hand, the throughput of line 42 decreased a large amount, while line 43 remained constant. Considering the MTBF, it is visible the throughput decreases as the MTBF is reduced in scenario 4, where the opposite is visible by increasing this failure rate.

Table 4.9: Throughput under different arrival patterns – Current system (confidential).

Scenario	Throughput 41	Throughput 42	Throughput 43
C1			
C2, C3			
C4			
C5			

Furthermore, the output of the machine states is provided in Table 4.10.[9] In comparison with scenario 1, it is clear all machine states (excluding starvation) increase as arrival rates increased. Table 4.11 presents the blockage ratios associated with the three palletizers in the system. Here, the blockage ratio of palletizer 41 and 42 increased in scenarios 2 and 3, while that of palletizer 43 hardly changed. Considering the MTBF experiments, it is noticeable that the machine states barely changed compared to the current scenario C1.

[9] The blockage ratio of the shrink wrapper is registered as not applicable since the work station behaves as the model exit due to the scope of this study (see Section 4.1).

Table 4.10: Machine states under different arrival patterns – Line 41 (*confidential*).

Machine	Scenario	Processing ratio	Starvation ratio	Blockage ratio	Failure ratio
Packer	*C1*				
	C2, C3				
	C4				
	C5				
Palletizer	*C1*				
	C2, C3				
	C4				
	C5				
Shrink wrapper	*C1*				
	C2, C3				
	C4				
	C5				

Table 4.11: Palletizer blockage ratios under different arrival patterns (*confidential*).

State	Scenario	Palletizer 41	Palletizer 42	Palletizer 43
Blockage ratio	*C1*			
	C2, C3			
	C4			
	C5			

4.2.4 Verification and Validation of the Simulation Model

In Section 3.2, it has already been emphasized that verification and validation are highly important in research. Therefore, the input data have been verified and validated as every effort has been made to ensure that the data was sufficiently accurate. The techniques used are also described in Section 3.2. In addition to the input data validation, the simulation model has been continuously assessed on reliability as well. According to the literature (see Section 2.5), white- and black-box validation is recommended as appropriate tools for this assessment.

Verification and White-box Validation

All three white-box testing methods, as proposed in Section 2.5, have been applied to this simulation. Initially, the code has been continuously checked and examined by using a debugger and visual checks. These techniques ensured a deeper understanding of the code. Moreover, the logic of the model and behavior against the real-world have been investigated by these visual checks. The behavior of each element has been analyzed by stepping through the model event by event and predicting events (e.g., dispatching priorities). In addition, the current model in its final version has been presented to the staff of Heineken (i.e., operators and management) and fellow students for supervision. The last approach, regarding visual checks, that has been conducted is experimenting by creating extreme conditions. Extreme arrival rates have been created (see Section 4.2.2) which overlaps with the final technique: inspecting output results. The performance of the individual elements of the current model (under varying arrival rates) has been compared to the actual results.

It is difficult to compare the machine states of the model to reality as the real-world data is a collection of the system's performance under different circumstances. The current system, on the other hand, only takes place in the steady-state of all lines operating. Nevertheless, these machine states (see Table 4.10) were still quite similar to the real data as.

Finally, a bottleneck analysis has been conducting on the simulation. Again, the turning point methodology has been used (see Figure 4.7). The bottleneck of line 41 was shifting towards the shrink wrapper by increasing arrival rates as the blockage ratios of all palletizers increased (see Table 4.11). Nevertheless, the palletizer is the bottleneck in this simulation model (mainly due to its high failure rate) which is the case in the real-world as well (see section 3.2). In addition to experimenting with the arrival rate, the effect of the shrink wrapper's MTBF has been examined as well. Therefore, the turning point method has been applied to scenarios 4 and 5. Still, the arrows between the adjacent machines indicated the palletizer as the core bottleneck of the model.

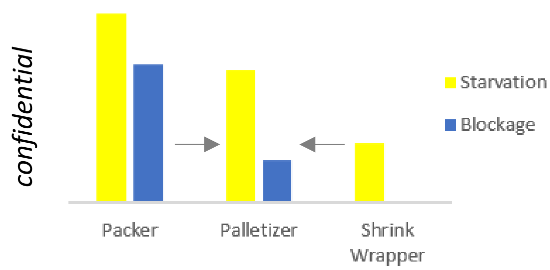


Fig. 4.7: Arrow-based bottleneck detection.

Black-Box
Once the model had been finished, the overall behavior of this stimulation has been assessed by using black-box validation. Here, the current model had been compared to the real-world by running it under the same conditions (see Figure 4.8).

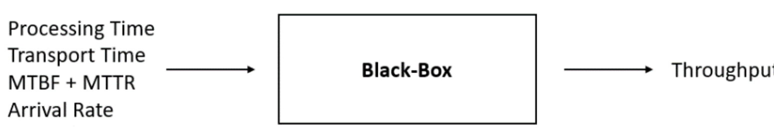


Fig. 4.8: Black-box validation of the simulation model.

The literature recommends comparing both the averages and spread of the data to the model output (see Section 2.5). However, only the averages have been examined as the standard deviation of the real-world plan efficiency was not available. The results show a significant similarity (see Table 4.12).

Table 4.12: Comparison of throughput rates – Simulation vs. real system (confidential).

System	Throughput 41	Throughput 42	Throughput 43
Simulation			
Plan efficiency			

4.3 Experiment Design

This section contains an explanation of all three experiments performed. These experiments included the following factors: switch regulation, sheet applicator failure and AGV dispatching rules. Moreover, the effect of an increased processing speed of the shrink wrapper has been tested. As mentioned in Section 1.4, speed modifications are excluded from this research study. Therefore, this experimental factor has been added in Appendix 9. Nevertheless, the key finding is provided in the concluding section of the solution design (see Section 4.5).

4.3.1 Experimental Factor: Switch Regulation

In Section 3.2, it has been explained that the switch regulation of the conveyor between the packer and palletizer is not properly distributed. To tackle this problem, the stacking process of pallets has been observed. Its pickup pattern is presented in Table 4.13. Here, for each pallet layer, all actions are performed in chronological order (i.e., from action 1 to 4).

Table 4.13: Palletizer stacking pattern.

Layer	Action 1	Action 2	Action 3	Action 4
1	6 packages right	3 packages left	3 packages left	-
2	4 packages right	2 packages left	4 packages right	2 packages left
3	6 packages right	3 packages left	3 packages left	-
4	4 packages right	2 packages left	4 packages right	2 packages left
5	6 packages right	3 packages left	3 packages left	-

In this experiment, the current regulation is the first scenario. Based on the stacking pattern, two new situations have been created. The second scenario is statically and follows the trend of the stacking distribution (see Table 3.1) by sending 6 packages to the right lane and 4 to the left thereafter. This process is constantly repeated. The other situation is more dynamic as it exactly follows the stacking pattern as presented in Table 4.13. For instance, this means 6 packages are sent to the right lane if this is required for the current stacking action.

4.3.2 Experimental Factor: Sheet Applicator Failure

The sheet applicator failure serves as the second experimental factor in this simulation. In Section 3.2, the correlation between sheets' quality and this failure has been explained. There, it has been showed that one can reduce this failure by sorting on the material. To simulate the effect of selecting on the quality, a different MTBF distribution has been used for the second scenario. The MTTR stays the same as the failure type remains unchanged. Moreover, a third scenario has been created including a new sheet applicator. The failure will occur at most 98% of the time according to the supplier. The exponential distribution has been used for the MTBF because it only requires the β value. This value has been determined by treating the failure as an experimental factor. The experimental input data of the sheet applicator failure are presented in Table 4.14.

Table 4.14: Sheet applicator failure as experimental factor.

Scenario	MTBF (minutes)		MTBF distribution
	α	β	
Current	0.53	2051	Weibull
Good material	0.53	5743	Weibull
New sheet applicator	-	8695	Exponential

4.3.3 Experimental Factor: AGV Dispatching Rule

The third experimental factor has been created with regard to the AGV dispatching rules. These priority rules have been described in Section 2.5. Some hybrid rules have been create based on their selecting procedures. The motivation and explanation are described in short:

- Current Scenario: SPTF is the main priority criteria. This is supplemented by the FIFO rule if no priority can be given based on the first rule (e.g., the processing times of lines 41 and 42 are identical). However, if the buffer utilization of the output buffer of line 43 is equal to 1, the FIFO rule is leading. Moreover, this line is always selected if its buffer utilization is greater than 2.
- Modified Current Scenario: The pickup priority is determined based on the SPTF rule, however, the FIFO rule is used if no choice can be made based on the processing time alone. In addition, the FIFO rule is leading if the output buffer utilization of line 43 is equal to 3.
- SPTF rule: This rule is never used alone as the processing times of lines 41 and 42 are identical. Therefore, a supplementary rule is used if no priority can be given based on the SPTF principle alone.

The complete set of dispatching rules used, is the following:

- Current Scenario
- Current Modified
- FIFO rule
- SPTF + FIFO rule
- SPTF + SD rule
- SPTF + LD rule
- SD rule
- LD rule
- SAST rule
- SAST + LACP rule
- GWTIQ rule

4.4 Results of the Experimentation

In this section, the results of the experimental stage have been provided. The throughput rates of all lines are presented. Moreover, relevant blockage, starvation and failure ratios are provided as well.

4.4.1 Experiment Results: Switch Regulation

The most relevant results with regard to the scenario testing of the switch regulation are presented in Table 4.15. It is visible that both experiments (i.e., static and dynamic) created an increased throughput for line 41 and slightly decreased throughput for line 42. In addition, the blockage and starvation ratio of the packer and palletizer, respectively, decreased. The throughput of line 41 increased the most during the dynamic approach, namely *+0.48%* (i.e., X/X (*confidential*))

Table 4.15: Throughput, blockage and starvation – Experiment: switch regulation (confidential).

Scenario	Throughput 41	Throughput 42	Throughput 43	Blockage Packer	Starvation Palletizer (41)
C1					
Static					
Dynamic					

4.4.2 Experiment Results: Sheet Applicator Failure

From the results in Table 4.16, it is clear that both experiments increased the throughput for line 41 and decreased the failure ratio for its palletizer. Based on these results, the highest throughput rate is acquired by filtering on material quality (*viz., +1.61%*). As packaging line 41 performed better, the throughput of lines 42 and 43 decreased and stays unchanged, respectively.

Table 4.16: Throughput and palletizer failure ratio – Experiment: sheet applicator failure (confidential).

Scenario	Throughput 41	Throughput 42	Throughput 43	Failure Palletizer (41)
C1				
Good material				
New sheet applicator				

4.4.3 Experiment Results: AGV Dispatching Rules

Table 4.17 shows that the best throughput rate for line 41 is noticeable under the (SPTF +) SD rule (*viz., +2.10%*) and SPTF + FIFO rule. The worst throughput for this packaging line took place under the LD rule. For line 42, the best throughput rate has been observed during the SPTF + FIFO , SPTF + LD and LD rules, while the worst throughput occurred under the Current and FIFO rules. Finally, packaging line 43 experienced the highest throughput rate by using the LD, GWTIQ and Current Modified rules. The least throughput was generated during the SPTF priority rule. Based on the output KPIs, the largest overall improvements occur while using the Current Modified rule and SAST rule (*viz., +0.86%*). Moreover, the shrink wrapper experienced the least starvation under the SPTF + FIFO, SPTF + LD and SAST dispatching rules.

Table 4.17: Throughput – Experiment: AGV dispatching rules (confidential).

Scenario	Throughput 41	Throughput 42	Throughput 43	Blockage Palletizer 41	Blockage Palletizer 42	Blockage Palletizer 43	Starvation Shrink Wrapper
C1							
Current Modified							
FIFO							
SPTF + FIFO							
SPTF + LD							
SPTF + SD, SD							
LD							
SAST							
SAST + LACP							
GWTIQ							

4.4.5 Experiment Results: Combining Experiments

Finally, several experiments have been executed regarding the combination of experimental factors. It is clear that the throughput rates during the dynamic approach were the highest with regard to the switch regulation experiments. Concerning the sheet applicator failure experiment, material selection provided the highest overall throughput. Therefore, these modifications have been used in the combined experiment.

Regarding the dispatching rules, on the other hand, the highest throughput for line 41 has been experienced under the SPTF + SD rule. However, as this study aims to increase the throughput of line 41 without reducing the performance of the other lines, it is also relevant to consider the total system. Then, the Current Modified and SAST priority rules performed best based on the overall throughput rate (viz., +3.22% for line 41).

To find the optimal solution, it has been decided to perform three new experiments including these priority rules and the optimal findings of the switch regulation experiment (i.e., dynamic approach) and sheet applicator experiment (i.e., material selection). Table 4.18 presents the results of these experiments. Again, the highest throughput for line 41 is acquired under the SPTF + SD rule, while the highest overall throughput (or system throughput) is generated under the SAST rule in experiment 17.

Table 4.18: Throughput – Experiment: dispatching rules under optimal setting (confidential).

Scenario	**Throughput 41**	**Throughput 42**	**Throughput 43**	**Blockage Palletizer 41**	**Blockage Palletizer 42**	**Blockage Palletizer 43**	**Starvation Shrink Wrapper**
Current							
Dynamic + Good material + SPTF + SD							
Dynamic + Good material + Current Modified							
Dynamic + Good material + SAST							

4.5 Alternative Solution Regarding OPI

The experiments proved that there is enough room for improvement of both lines 41 and 42. As both lines are identical and face the same problems, it is assumed that the improvement of line 41 is equal to that of 42. Therefore, the alternative solution (including all modifications) is relevant for both lines. By comparing the current state to the alternative solution, it is clear that the throughput increased by 3.22 % (i.e., X/X (*confidential*)). However, as the model is set in the steady-state, it has been assumed (in consultation with the management) that this scenario takes place around 90% of the time. This means that an improvement of 2.89% (0.90 ∗ 3.22) throughput has been realized. The improved OPI values are computed as is shown below.

Improved OPI (line 41) *= Current OPI ∗ (1 + realistic throughput) = X% (confidential)*
Improved OPI (line 42) *= Current OPI ∗ (1 + realistic throughput) = X% (confidential)*

From Table 4.19 it is visible the OPI de increased by **1.57%** and **1.58%** for lines 41 and 42, respectively. In section 4.4, the improvements in the individual modifications used in experiment 17 have already been expressed in throughput. These improvements have been expressed in OPI by using the same calculations as above (see Table 4.20).

Table 4.19: Effect of the alternative solution on the OPI (confidential).

Criterion	Line 41	Line 42
Steady-state throughput	+ 3.22%	
Realistic throughput	+ 2.89%	
Current OPI		
Improved OPI		
Difference in OPI	*+ 1.57%*	*+ 1.58%*

Table 4.20: Effect of the individual modifications on the OPI (confidential).

Criterion	Dynamic approach		Good material		SAST rule	
	Line 41	Line 42	Line 41	Line 42	Line 41	Line 42
Steady-state throughput	+0.48%		+1.61%		+0.86%	
Realistic throughput	+0.44%		+1.45%		+0.77%	
Current OPI						
Improved OPI						
Difference in OPI	*+0.24%*		*+0.79*		*+0.42%*	

Now it is interesting to express the effect of the alternative solution in terms of reduced operating times. To calculate these operating times, the output is computed by the equation below at first. The changeover time and quality losses are included in the output, which makes the difference with the throughput. Moreover, the production plan during mid-season is considered. Then, the lines operate 7 days 16 hours per week (i.e., 112 hours).

$$\textbf{\textit{Output}} = \textit{Capacity (line)} * \textit{OPI}$$

From this output, the available capacity is determined by the equation below. Table 4.21 presents the results of these calculations.

$$\textbf{\textit{Available capacity}} = \textit{Output} * \textit{Operating time}$$

For both packaging lines, the operating times decreased by **209 minutes** per week. This can be explained by taking line 41 into consideration: previously 112 hours were required to make X (*confidential*) draught kegs, now this is possible within 108.50 hours as the output increased.

Table 4.21: Output and operating time – Current and improved system (confidential).

Criterion	**Line 41**		**Line 42**	
	Current	+ 1.75% OPI	Current	+ 1.76% OPI
Capacity				
OPI				
Output				
Operating Time	112 hour	*108.50 hours*	112 hour	*108.50 hours*

4.6 Summary of the Solution Design

A conceptual model of the real-world has been designed in the first step of the solution design. The model has been created based on the general objective of this study: to improve the OPI by increasing throughput. Then, the scope and level of detail have been determined. In addition, the model consists of five input variables (i.e., processing times, transport times, failures and arrival rates) and two output variables (i.e., average throughput, machine states). Finally, several simplifications and assumptions have been established to accelerate model development, tackle a lack of data and implement beliefs about the real-world in the model.

The simulation model has been constructed after the conceptual model had been developed. Initially, its experimental setup has been determined, namely the nature, warm-up period, run length and number of replications. Thereafter, the output data (including varying arrival rates and MTBF) have been analyzed to obtain deeper insights into the model's sensitivity and reliability. This data have been verified and validated by white- and black-box validation.

Furthermore, three experimental factors have been implemented to simulate the effects of these potential solutions. These experiments concern the switch regulation, sheet applicator failure and AGV dispatching rules.

Moreover, a fourth experiment has been conducted regarding the effect of increased speed at the shrink wrapper. Based on the results, it can be concluded that the current performance is more affected by its failure rate than its speed. Therefore, Heineken should focus on the failure rate to improve the overall system performance.

Table 4.22 shows the results of experiments 1, 2 and 3. From the analyzation, it is clear that the OPI was the highest during the dynamic approach (viz., +0.24%) and the selection of good material (viz., +0.79%) of the first and second experiments, respectively. The SPTF + SD priority rule generates the highest throughput rate from the perspective of line 41. The smallest average slack time rule, on the other hand, experiences the highest throughput and OPI (viz., +0.42%) considering the total system. As this study aims to improve line 41 without obstructing other lines, it has been decided to focus on experiment 17 in the following sections (i.e., including SAST rule). This alternative solution shows an increased throughput of +3.22% during the steady-state of the model. This equals an increased OPI of **1.57%** (line 41) and **1.58%** (line 42), which save **209 minutes** of operating time (per line) a week. it is visible that combining the 3 modifications gives a higher result than the sum of the modifications as an individual. For instance, 1.57% is greater than 1.45% (0.24% + 0.79% + 0.42%). This can be explained as the SAST provides room for improvement of the lines.

Table 4.22: Throughput – Considering all experiments performed.

Number	Scenario	Throughput 41	Throughput 42	Throughput 43
1	*C1*			
2	Static			
3	Dynamic			
4	Good material			
5	New sheet applicator			
6	Current Modified			
7	FIFO			
8	SPTF + FIFO			
9	SPTF + LD			
10	SPTF + SD, SD			
11	LD			
12	SAST			
13	SAST + LACP			
14	LWTIQ			
15	Dynamic + Good material + SPTF + SD			
16	Dynamic + Good material + Current Modified			
17	Dynamic + Good material + SAST			

5 Trade-offs

This section evaluates the (financial) trade-offs regarding the key findings of the solution design. Here, a distinction has been made between non-cash savings and cash-savings. Section 5.1 explains the non-cash savings and Section 5.2 the cash savings with regard to increased throughput. Thereafter, the costs of implementation are determined in Section 5.3. Finally, a conclusion with regard to the key findings of the cost reductions is provided in Section 5.4.

The calculations are performed with respect to experiment 17 (alternative solution), and packaging lines 41 and 42. The savings per individual modifications are added in Appendix 10 for convenience, however, and taken into account in section 5.4. Furthermore, the costs are not expressed in terms of energy costs as the required information is not stored for the lines investigated in this study. According to the process control department, this information is not stored as these lines contain a relatively low capacity. In addition, lost sales are neither included as it is out of the scope of HNS, and the current production capacity is greater than the demand on average.

5.1 Non-Cash Savings

Non-cash savings concern all cost savings that are not directly noticeable in the total balance sheet. For instance, a small improvement of 1% throughput does not mean 1% less salary is paid. However, the employees concerned can do other activities instead if an order is finished earlier. The planning department annually reviews and updates the work schedule. Therefore, it is plausible to assume that these cost reductions are experienced as non-cash savings this year, and cash-savings the year thereafter.

The costs of employees are the largest regarding relevant non-cash savings. Therefore, these non-cash savings are expressed as *direct labor cost reduction*. In order to compute the reduced costs, several variables are required. These are presented in Table 5.1.

Table 5.1: Given variables regarding reducing the costs of employees.

Variable	Line 41	Line 42
Personnel expenses	€X (*confidential*)	
Employees	367	
Employees present	5.5	5.5
Gross production time	4,948 hours	4,948 hours
Planned downtime	433 hours	495 hours

Using the information from Table 5.1 and *equation 3* below, the non-cash savings are computed. Therefore, the average salary costs in euros (see *equation 1* below) and the value of 1% OPI in hours (see *equation 2* Below) have been computed at first. All results are presented in Table 5.2.

$$1):\ \textit{\textbf{Average salary costs(€)}} = \frac{\textit{Personnel expenses}}{\textit{Employees}}$$

$$2):\ \textit{\textbf{1\% OPI (hour)}} = \frac{\textit{Gross prodution time-Planned downtime}}{\textit{100}}$$

$$3):\ \textbf{Non cash savings} = \frac{\text{Empoyees present} * \text{Average salary cost (€)}}{\text{1\% OPI (hour)}}$$

Table 5.2: Results of the computations regarding the non-cash savings of 1% OPI (confidential).

Variable	**Line 41**	**Line 42**
Average salary costs	€X	
1% OPI	45.15 hours	44.53 hours
Non-cash savings	€X	€X

From Table 5.2, it is visible that the non-cash savings for 1% OP contain €X (line 41) and €X (line 42) per year. The direct labor cost reduction of the alternative solution can be calculated by multiplying these values with the increased OPIs, which have been computed in Section 4.4. Table 5.3 shows the results. Hence, the expected annual non-cash savings for lines 41 and 42 contain **€X** (*confidential*) and **€X** (*confidential*), respectively.

Table 5.3: Non-Cash savings of the alternative solution (confidential).

Criterion	**Line 41**	**Line 42**
Increased OPI	+ 1.57%	+ 1.58%
Non-cash savings	€X	€X

5.2 Cash Savings

In addition, cash-savings per 1% OPI increase are determined. Cash-savings contain all cost savings that are directly visible and can be set aside. In collaboration with the strategy department, it has been decided that the most direct costs can be saved by focusing on warehousing. Transport and internal (i.e., Heineken Zoeterwoude) storage costs are excluded as these are fixed. However, this does not apply for external storage (i.e., storage abroad), where most demand comes from. Heineken can reduce its build to stock by increasing its OPI values, which implies costs can be saved due to shorter lead times.

First, the available capacity per week should be determined in order to calculate stock reduction. The output is already determined (see Section 4.5). The demand and available time are already given and the available capacity is computed by the equation below.

$$\textbf{\textit{Available capacity}} = \textit{Output} * \textit{Total time available}$$

Now the yearly stock reduction in the number of kegs can be determined by adding up the stock reduction of all weeks. The calculation of this stock reduction is explained based on the fictional numbers in Table 5.4. Here a total available time of 192 hours has been applied. The “need for stock” is calculated by subtracting the available capacity from the demand. Now the stock reduction can be calculated, which is 8,139 kegs (66,421 – 58,283) in this example.

Table 5.4: Example of stock reduction computations (confidential).

Scenario	**Demand of the week**	**Output**	**Available capacity**	**Need for stock**
Current	398,120 kegs			66,421 kegs
+ 1.57 % OPI	398,120 kegs			58,283 kegs

The same computations have been performed on a real-time planning schedule including the entire year. The results show a stock reduction of X kegs (X pallets) per year for line 41 and X kegs (X pallets) for line

42. The holding cost per pallet include €X (*confidential*), which means that €X (*confidential*) is directly saved.

5.3 Costs of Implementation

The programming skills that are required for the implementation of the switch regulation modification and improved dispatching priority are out of scope for this research. Therefore, a programming expert of Pa-/Pi engineering is required in order to implement the findings of the alternative solution.

The improved switch regulation has already been implemented at the conveyor line of Heineken. It took the executive engineer approximately four hours to observe, understand and implement this modification. Considering the average salary costs (i.e., €X per hour), the expenses were around €X (*confidential*). In addition, it is expected that the modification with regard to the dispatching rules will take approximately two working days to program. This will cost €X (*confidential*) in personnel expenses.

Furthermore, the quality department of the brewery has already been contacted regarding the sheet applicator failure. They have to contact the supplier to report poor material quality. It is assumed this takes approximately four hours, which is €X (*confidential*) in personnel expenses.

This amounts to a total cost of **€X** (*confidential*). However, these costs only contain non-cash expenses as they contain in-house personnel wages.

5.4 Conclusion of the Trade-offs

This section presents the cost savings per modification (see Table 5.5) based on the computations in Appendix 10 and the cost savings by implementing the alternative solution (see Table 5.6). In Section 1.4, the following limitation to this research has been mentioned: all investments made must be earned back within a time of two years because this is a principle of Heineken. Therefore, the total savings are shown within a timeframe of two years. Both non-cash savings and cash savings are merged as total savings. Due to the annual revision of the work schedule, it is assumed non-cash savings will be cash savings for the next years.

Table A.8: Overview of the total cost savings per modification (confidential).

	Criterion	**One year**	**Two years**
Switch Regulation: dynamic approach	Non-cash savings Cash savings Costs of implementation ***Total savings***		
Sheet applicator failure: sorting good material	Non-cash savings Cash savings Costs of implementation ***Total savings***		
AGV dispatching rules: SAST rule	Non-cash savings Cash savings Costs of implementation ***Total savings***		

Table 5.6: Overview of the total cost savings by implementing the alternative solution (confidential).

	One year	**Two years**
Non-cash savings		
Cash savings		
Costs of implementation		
Total savings	€	€

Figure 5.1 presents a cause and effect matrix concerning these total savings. It is visible that the alternative solution creates a larger profit than the sum of the cost savings per modification. This can be explained as the SAST dispatching rule ensures more throughput for the system as a whole.

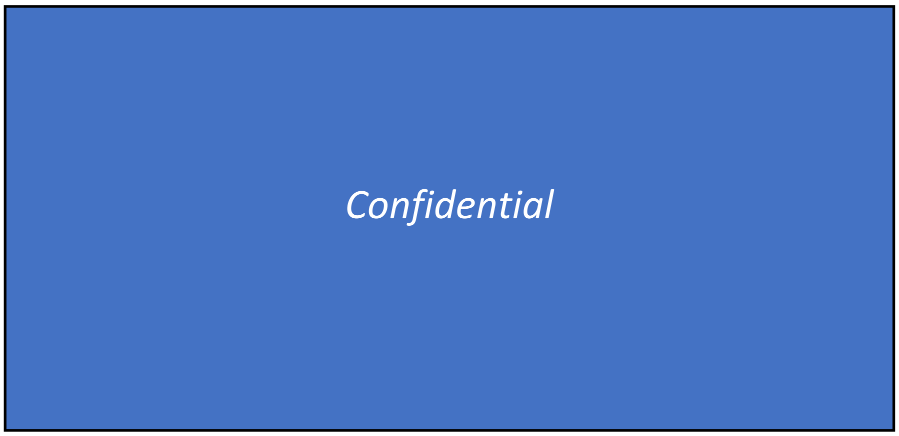


Fig. 5.1: Cost and effect matrix concerning the modifications and alternative solution.

In addition to trade-offs with regard to costs, (mental) health and safety should be considered as well. A positive influence of the modifications is an improved and safer shop floor for the operators involved. They experience the sheet applicator failure as really stressful as it is a frequently occurring failure. Moreover, the switch regulation has a deviation to the right lane which causes problems when the machine is emptied. Only the left lane can empty the remaining cans. As a result, operators have to climb into the machine to empty it. This clashes with Heineken's health and safety policy as the company endeavors to eliminate accidents from its workplaces (Heineken NV, 2011).

6 Conclusion

This section finishes the research study by concluding the research conducted at packaging line 41 of the Heineken Brewery in Zoeterwoude. Moreover, Section 6.1 of this conclusion provides the answer to the research question (see Section 1.3) which is as follows:

How to improve line performance, by reducing the core bottleneck, of packaging line 41 at Heineken Zoeterwoude?

Apart from line 41, this study also applies to packaging line 42 as it is an identical line that faces the same problems. Therefore, regarding both lines, this study aimed to improve the current performance through line performance optimization. This improvement is expressed in OPI as it is the main Key Performance Indicator of Heineken.

Concerning this section, a list of recommendations with regard to this work has been provided in Section 6.2. Whereafter possibilities for further research are explained in Section 6.3. Finally, Section 6.4 evaluates this thesis based on its contribution to the practice and literature.

6.1 Conclusion

The aim of this study was to improve the current line performance of packaging line 41 without obstructing other lines. Data analysis has been executed to identify the bottleneck as it is the weakest link in the system. This analysis has shown that the palletizer is the constraining machine. The overall performance can be drastically increased by actively focusing and controlling this bottleneck. Therefore, the palletizer and adjacent processes have been thoroughly investigated to obtain deeper insights for potential solutions. The results indicated the following three problems that can be improved:

(1) incorrect switch regulation – creates starvation at the palletizer as the distribution of the switch's output pattern does not match the palletizer's input pattern;
(2) frequently occurring sheet applicator failures – are aggravated by using poor material. This causes blockages upstream the process as the palletizer stops;
(3) AGV dispatching rules – by using an appropriate priority rule, the system's total throughput can be improved as the AGV regulates the throughput of three connected lines.

A simulation model, including these three experimental factors, has been created to find the optimal solution. An alternative solution has been created, which states that all factors should be modified. According to this experiment, the dynamic settings are appropriate for the switch regulation. These settings make sure that the switch output pattern follows the input pattern of the palletizer. Moreover, it is important to inspect the quality of material to drastically reduce the amount of sheet applicator failures. Finally, the Smallest Average Slack Time rule performs best compared to all other dispatching rules tested. Slack is the amount of time that an activity can be delayed without delaying the system. Heineken should apply this priority rule, which ensures a higher throughput for the system as a whole.

The results are expressed for packaging lines 41 and 42 as these are identical lines and both face the same problems. The alternative solution shows an increased throughput of **+ 3.22%** during the system's steady-state, which is equal to **+ 1.57%** and **+ 1.58%** OPI for lines 41 and 42, respectively. Moreover, the total reduced operating time a week contains **209 minutes** per line. Based on the trade-offs regarding costs a total amount of **€X** (*confidential*) is saved once this modification is implemented. Moreover, it has been discussed that the implementation is beneficial in terms of ergonomics as well because both stress and safety will be improved.

The Theory of Constraints is the leading theory in this study. It is a systematical approach developed to earn more profit by increasing the throughput of a process or operation. Considering this theory, the final step is to evaluate whether the constraint has been broken. Again, the turning-point methodology has been applied to the results of the alternative solution. This is a bottleneck detection technique that aims to utilize the production line's blockage and starvation probabilities to find the core constraint. The method shows that the palletizer is still the bottleneck machine of the system; despite its improved performance. Therefore, the TOC states Heineken should continue elevating this machine until the constraint is broken.

6.2 Recommendations

In addition to the recommendation to implement the alternative solution, some other inefficiencies and potential points of improvement are found during this research study. An overview of these recommendations is provided below:

- Develop a sense of ownership: Heineken is already focusing on creating ownership as the company believes it will be a key factor in its success. Nevertheless, improvement is still possible as employees do not always comply with this responsibility. For instance, operators already had a gut feeling about material causing the sheet applicator failure, however, the usual procedures to tackle the problem were not thoroughly performed. Moreover, it is also important to create awareness of the outcome of an action. A relevant example is the incorrect data-registration (i.e., incorrect registration of blockages caused by the palletizer) due to ill-considered decisions. Therefore, Heineken should further develop this philosophy by creating an environment where people are given authority, resources and time to make sound decisions (Kulkarni & Dabade, 2013).

- Hire extra Pa-/Pi engineers: Employees have to report inefficiencies by a label to comply with their ownership. These labels are regarding varying aspects such as machine issues and inaccurate data registration. However, there are not enough Pa-/Pi engineers compared to the number of labels currently created. As a result, it can take several months before action is taken, which is considered as demotivating by the operators. This speed can easily be increased by hiring extra Pa-/Pi engineers. Reallocation of resources is recommended if it is decided not to invest in this. In addition, it is suggested to provide more insights into the waiting time, once a labeled is created. Understanding of employees involved will increase through creating shared planning.

- Develop interdepartmental communication: The Heineken Company should focus more on interdepartmental communication as it will create added value by knowing each other's role in the chain. This is really critical since the packaging and palletization department work separately, however, have a large effect on each other. Nowadays friction occurs as both parties do not know what is happening "behind the wall". Therefore, Heineken should encourage effective communication by bringing together its employees through upward and downward flow of communication and especially by creating a peer-to-peer dialogue among employees (Gondal, Shahbaz, & Shahbaz, 2012).

- Improve data registration at MES: The data registration system MES should be improved based on both accuracy and gaining more insight. Incorrect data-registration (see Appendix 4) has been noticed several times during this research. This makes the data unreliable. Moreover, the current selection of parameters is limited. For instance, machine warm-up speeds are not considered in the data strings and neither are processing times. Based on these issues, it is recommended to clean up and further develop the data system. Besides, it is recommended to increase the understanding among employees with regard to their contribution to data entry. Once the employees see the bigger picture, it is likely that they will more consciously handle the data.

- Optimize overall line balance: Now more insights have been obtained into the current line balance, it is clear that it does not create the V-shape when plotting the line's production capacity. This means that the buffer strategy is not properly used as it does not ensure products at the infeed and space at the discharge of the critical machine currently. This is why it is recommended to revise and where possible improve the current line balance with regard to buffer and capacity modifications.

6.3 Further Research

In this section, various suggestions for further research are presented. These ideas for further research are listed:

- Improve performance of shrink wrapper: Based on the conclusion of Section 4.6, it is clear a large amount of time is wasted due to failures at the shrink wrapper. As the shrink wrapper is the meeting point of three production lines, Heineken can improve the overall system performance by focusing on this machine.

- Optimize overall line balance: This suggestion has been explained in Section 6.2 and is considered as a relevant subject for further research.

- Improve the pallet supply: The pallet supply regularly causes failures while picking up empty pallets. This mechanical issue should be solved as it negatively affects the overall line performance.

6.4 Contribution to Practice and Literature

Finally, this research study is finished by evaluating its contribution to practice and literature.

Currently, the switch modification has been implemented as recommended, and the quality department of the brewery has been informed about the relationship between material quality and sheet applicator failures. The other recommendations, as proposed in Section 6.2, are not implemented yet. During this study, there was a large amount of cooperation with different departments. Various projects have been started in this way such as creating the current line balance including v-graph in collaboration with the Pa-/Pi engineers and starting an *MSAS* (Minor Stop Analysis Sheet) together with the palletizer operators.

Moreover, this study has developed an Excel tool to predict accumulation times. Finally, it has been ensured to stop data manipulation by explaining the effect to the team involved.

In a simulation study regarding the manufacturing environment, it is not typical to take the human role into consideration. To illustrate the importance of this human touch to the research, this thesis illuminates the human role involved in the manufacturing environment. For instance, the influence of humans on data processing has been explained. Besides, the counteractions and corresponding procedures are described. Hence, in addition to a theoretical case study, the human role is also included to stress its role in manufacturing. In follow-up research, the human touch will be discussed in more detail with regard to data and manufacturing.

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Appendices

Appendix 1: OPI Composition

In this appendix, the detailed structure of the Operation Performance Indicator (OPI) is defined in detail.

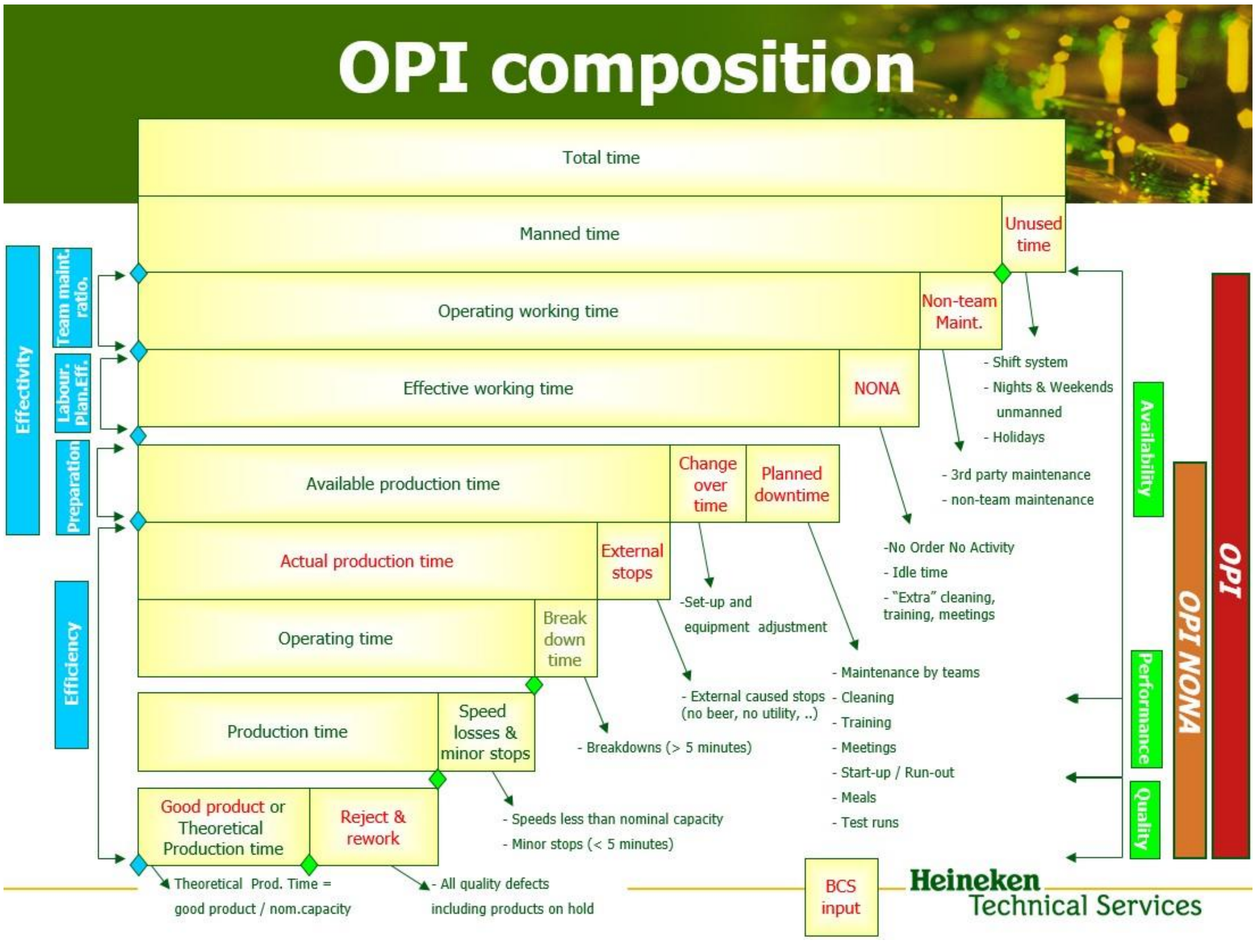

Fig. A.1: Visualization of the OPI construction (HNS, 2010).

Appendix 2: Example Calculation OPI

From Section 3.1.7, it is clear that the OPI is a product of the availability, performance and quality. The OPI can be calculated by computing the equations of these criteria. In this appendix, an example calculation is given including virtual numbers to make these computations clear.

Total time: 510 minutes
Unmanned shift: 30 minutes
Meetings: 20 minutes
Cleaning: 25 minutes
Change over: 35 minutes
Breakdowns: 40 minutes
Speed losses and minor stoppages: 50 minutes
Good products: 22,610 kegs
Line capacity: 2,800 kegs / hour

Using the above information, the following results have been calculated:

Manned time: 480 minutes (510 - 30)
Operating time: 360 minutes (480 - 20 - 25 - 35 - 40)
Production time: 310 minutes (360 - 50)

Since the line capacity is 2800 kegs per hour, it would theoretically take 485 minutes (22,610 / 2,800) to produce 22,610 good products. In this example, it took 510 minutes to produce this amount.

The following OPI is calculated based on these results:

$$\textbf{\textit{OPI = Availability}} * \textbf{\textit{Performance}} * \textbf{\textit{Quality}} = \frac{360}{480} * \frac{310}{360} * \frac{485}{510} * \textbf{\textit{100 \% = 61 \%}}$$

Appendix 3: Shrink Wrapper as Meeting Point

Section 3.2 mentioned that the machine capacity of the shrink wrapper is varying. This can be explained as its available capacity depends on the output of the three production lines. The underlying principle is simple, if a line generates more output, more capacity is required at the shrink wrapper.

At first, the data of the average palletizer output of the lines has been gathered. The plan efficiency has been determined by the strategic planning department based on the production results. As packaging line 41 and 42 are identical, both lines have the same planned average output. Due to the pallet size product mix, their most critical scenario have been used for this research. Based on all orders of 2019, this scenario takes place 62% of the total production time. As input for the line 43 calculations, a pallet size of 49 has been taken as it is the most common used pattern; 45% of the production time. The expected outcomes are calculated by using the equation below. The results are presented in Table A.1 below.

$$\textbf{\textit{Capacity (pallets/hour)}} = \frac{\textit{Capacity (parts/hour)}}{\textit{Pallet size}}$$

Table A.1: Maximum production output per line (confidential).

Packaging Line	Capacity (parts/hour)	Pallet size	Capacity (pallets/hour)
41			
42			
43			
Total	-	-	

The capacity of the shrink wrapper is X pallets an hour (*confidential*). Therefore, this capacity does not meet the total maximum output of the three packaging lines combined, which is X pallets an hour (*confidential*). Currently, it is unclear what fraction of time this scenario occurs. It is estimated that it is less than 5% of production time. It is likely that this situation occurs relatively little since the average output of the lines combined does not meet the X pallets an hour (*confidential*). This is shown in Table A.2 below and explains the shifting bottleneck.

$$\textbf{\textit{Average output (pallets/hour)}} = Plan\ efficiency * Capacity\ (pallets/hour)$$

Table A.2: Expected production output per line (confidential).

Packaging Line	Plan efficiency	Average output (pallets/hour)
41		
42		
43		
Total	-	

Appendix 4: Incorrect Data Registration

By analyzing Heineken's data base MES, it became clear this data registration was not flawless. Some examples are provided in this appendix. Moreover, the tool has been presented with which data strings of blockages could be verified.

Specific Errors in the MES Database

- The data registration of the drying tunnel was disabled sometimes because the registration system was turned off. This usually occurs after a production stop. The inaccurate display has been encircled in Figure A.2. In this figure, the production stop is colored in purple.
- A blockage occurred at the packer (7:59-8:00 AM) due to a palletizer failure (Start: 7:57 AM). Operators were instructed by a process control operator to report these blockages as production stops (8:00-8:15 AM). This example is encircled in Figure A.3. As a result, this data modification causes inaccuracies and unusable data. Therefore, all data has been rectified manually by looking at the data labels (see Figure A.4). Since this is a highly time consuming process, the data used for this research is retrieved on April 2019. This was the most recent month and corresponded in terms of behavior with preceding months.
- The shrink wrapper wrongfully reports blockages, which became clear by empirical observation (see Figure A.5).

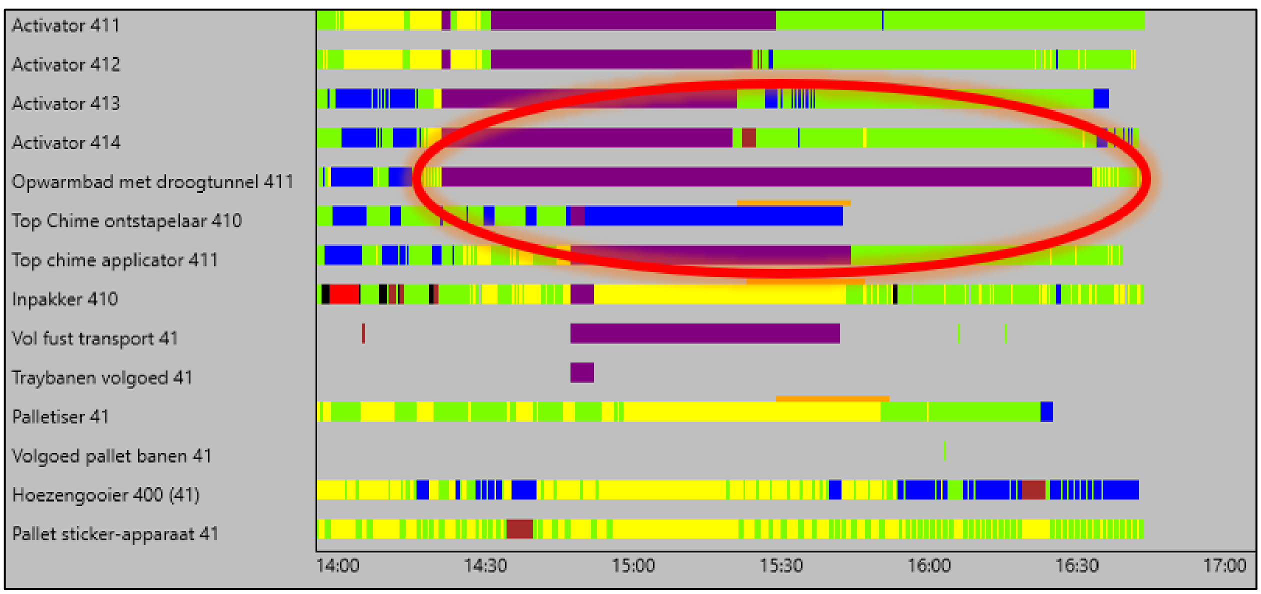

Fig. A.2: Incorrect data registration of the drying tunnel.

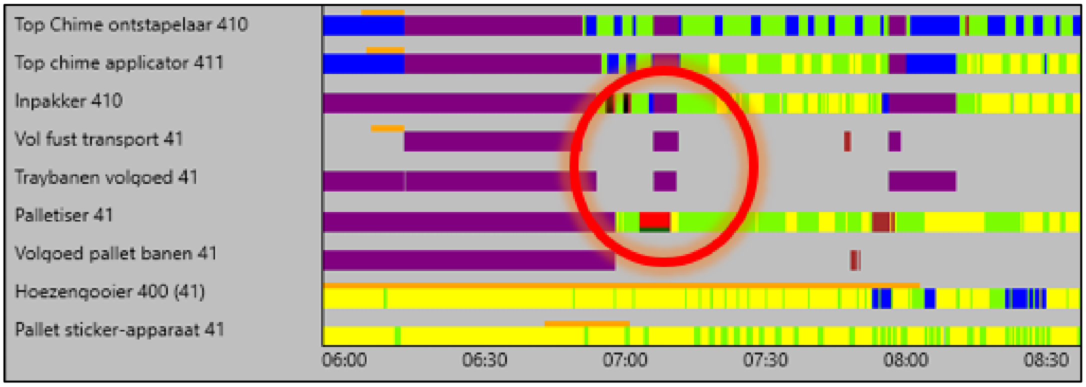

Fig. A.3: Incorrect data registration of the packer.

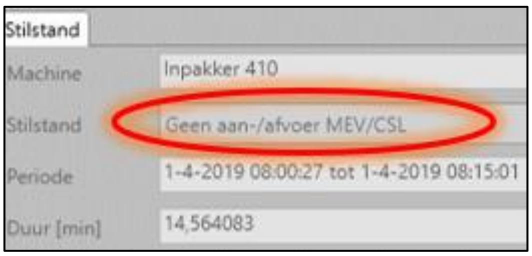

Fig. A.4: Example of a stoppage label.

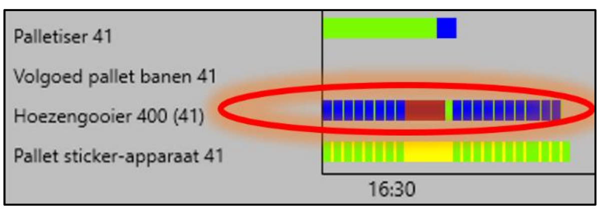

Fig. A.5: Incorrect data registration (blockage) of the shrink wrapper.

Tool for Verification of the Cause of Blockages

Since it turned out that it could occur stoppages were improperly labeled as a result of a palletizer failure, a tool has been created to verify the correlation of failures and blockages at the packaging line. The tool has been created to determine the failure cause based on buffer accumulating times and machine states. To measure this accumulation, HNS (2017) has created a distinction between downstream and upstream accumulation. According to their masterclass on line balancing, accumulation can be calculated following the steps below:

Upstream Accumulation

(*confidential*)

Downstream Accumulation

(*confidential*)

By applying the steps above a VBA tool have been created to calculate relations between machine failures and blockages and/or starvation. A print screen is provided in Figure A.6.

```
'Double loop
For x = 2 To lastRow_inpakker

        totalDur = totalDur + Cells(x, 5).Value

    For i = a To LastRow_startStoring

        'If volloopstarttime is in the timeslot of -3min/0,5min.
        If (Cells(x, 4).Value - valmin * 2 <= Cells(i, 2).Value And Cells(x, 4).Value - valmin * 0.5 >= Cells(i, 2).Value) ~
        Or (Cells(x, 4).Value - valmin * 0.5 <= Cells(i, 3).Value And Cells(x, 4).Value + Cells(x, 5).Value >=          ~
        Cells(x, 5).Value >= Cells(i, 3).Value) Then
            Cells(x, 6).Value = Cells(i, 1).Value
            'Cells(x, 7).Value = Cells(x, 5).Value

        Else: Cells(x, 6).Value = "no"
        End If

        'make loop faster and end to prevent overwriting; This code is not leak free, however, much faster.
        If Cells(x, 6).Value = Cells(i, 1).Value Then a = i
        If Cells(x, 6).Value = Cells(i, 1).Value Then Exit For
        If Cells(x, 4).Value <= Cells(i, 2).Value Then Exit For

    Next i

            'Splitting up failures
             If Cells(x, 6) = "Stilstand" Then
                Stilstand = Stilstand + Cells(x, 5).Value
            ElseIf Cells(x, 6) = "Volloop" Then
                Volloop = Volloop + Cells(x, 5).Value
            ElseIf Cells(x, 6) = "Status onbekend" Then
                Onbekend = Onbekend + Cells(x, 5).Value
            End If

Next x
```

Fig. A.6: Print screen of the blockage tool for the packer-palletizer correlation.

Appendix 5: Images of the Sheet Applicator Failure

In the pictures below, the sheet recordings of the sheet applicator failure has been presented (see Figure A.7 and Figure A.8). At first, the sheet applicator picks up two sheets instead of one (1.). Since the vacuum power is not great enough to elevate two sheets at once, the first sheet drops (2.). As a result, the second sheet also drops (3.) and ends up next to the pile of sheets (4.). As a result, the sheet applicator picks up multiple sheets, which disrupts the process and causes a machine failure (5.).

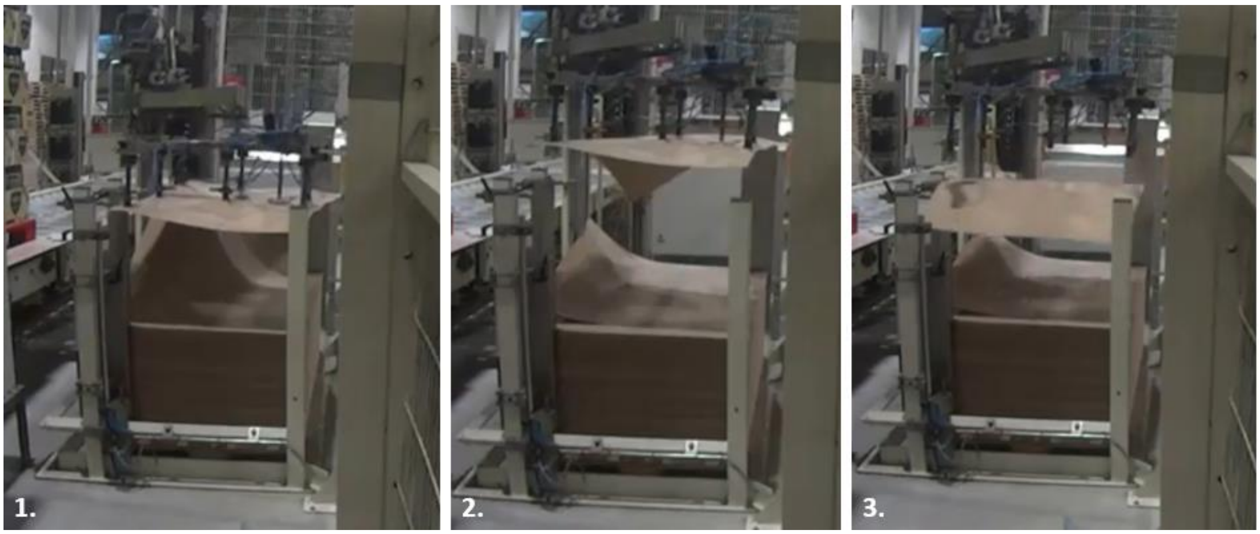

Fig. A.7: Sheet applicator failure step 1 to 3.

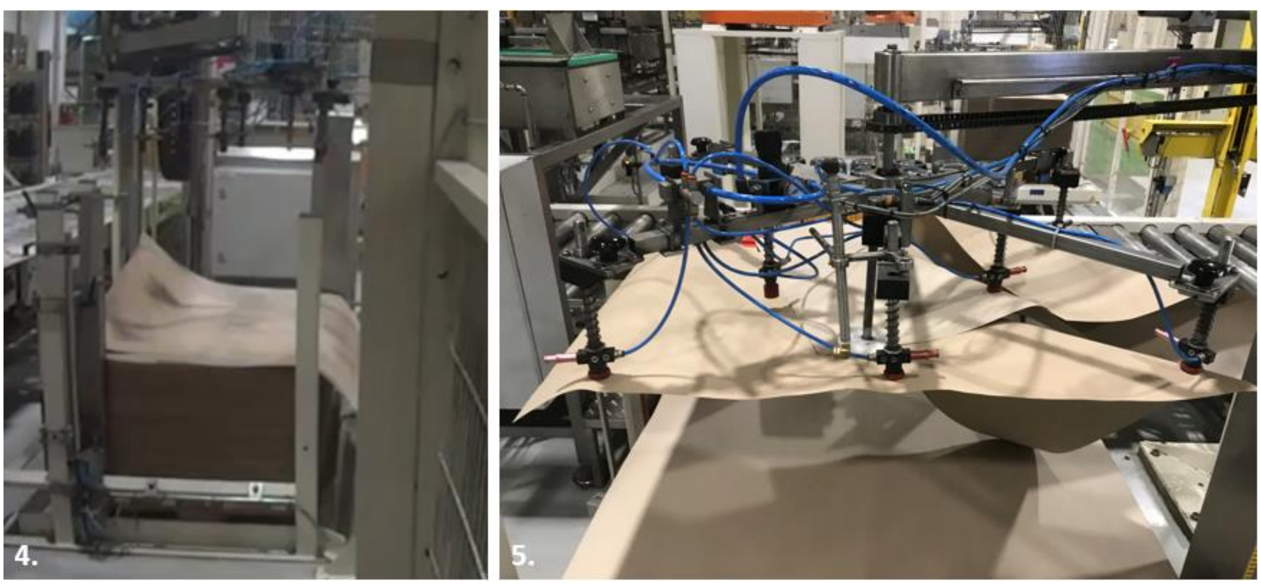

Fig. A.8: Sheet applicator failure step 4 and 5.

Appendix 6: Poor Material Causing Sheet Applicator Failures

In this appendix, pictures of poor quality sheets have been provided. Using this bad quality material causes sheet applicator failures. Clearly visible is its corrugated structure (see Figure A.9). Moreover, its relative humidity is considerably lower than normal as it is around 25%. The average relative humidity at home is approximately 40-50%, which is also desirable for this material according to the quality department of the brewery.

Fig. A.9: Sheets of poor quality.

Appendix 7: Flow Chart of Palletizer Stacking Pattern

In this appendix, a flow chart has been provided describing the process of the palletizer stacking pattern.

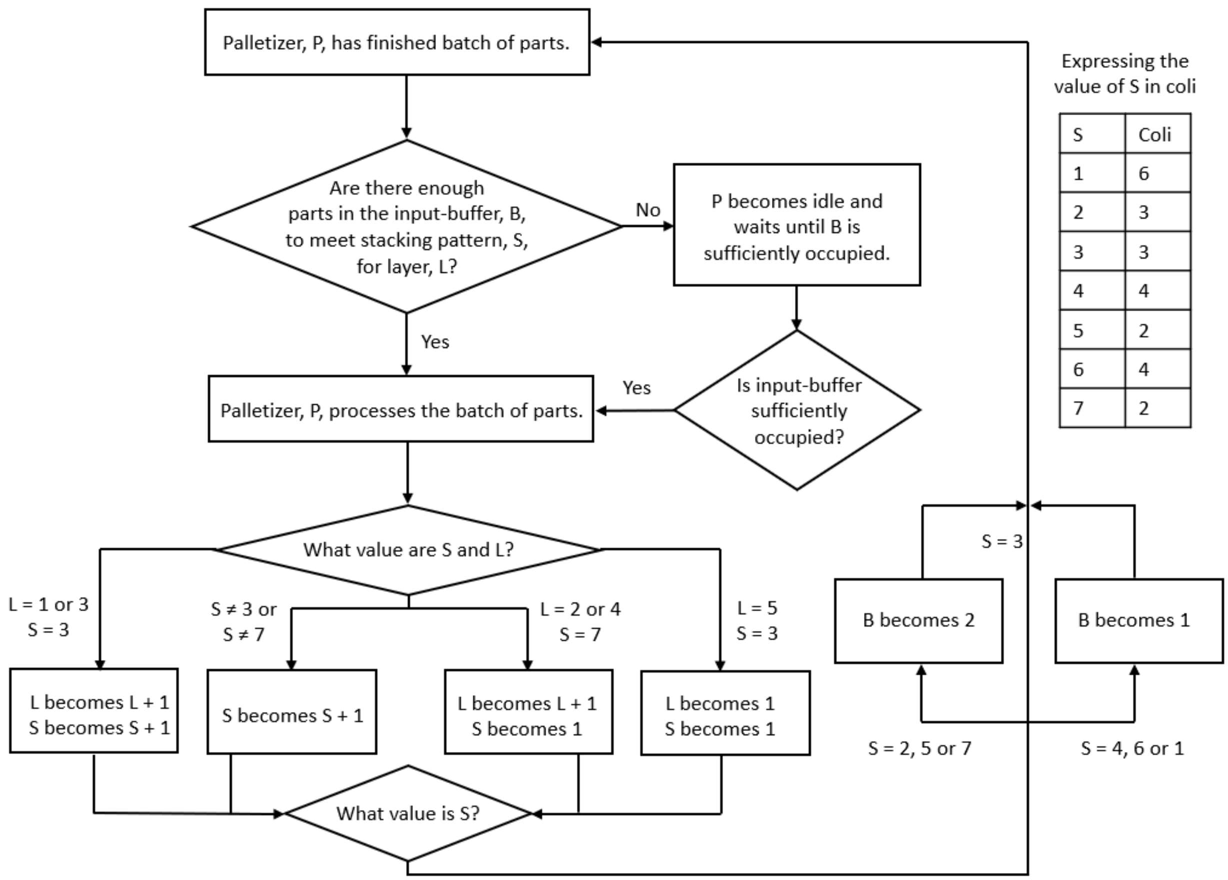

Fig. A.10: Flow chart of the palletizer stacking process.

Appendix 8: Empirical Data to the Distributions of the Simulation Input

In this appendix, the failure distributions of the machines used in the simulation model are presented. These distributions have been applied to the sample datasets of the Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR) and Mean Time of Starvation (MTOS). A suitable distribution has been selected based on its fit and behavior according to literature as has been described. In Figure 4.11, an example of the Chi-square as executed in Excel has been provided.

Ordering MTBF
1
1
1
1
1
2
2
2
2
2
2
3
3
3
3
3
3
3
4

Weibull:	
alpha	0.42677
beta	863.8959
Count	259
sqrt(Count)	16.09348
Bins	17
Max Value	43741
Chi Value	**27.58711**
>	
Critical Value	**24.63202**

Bins	***Bin***	***Frequency***	**real**	**dist**	**chi**
20	20	57	0.181653	47.04814	2.10507
40	40	27	0.236219	14.13263	11.71539
60	60	12	0.274128	9.818447	0.484718
80	80	6	0.30388	7.705679	0.377558
100	100	4	0.328623	6.408527	0.905201
120	120	4	0.349923	5.516557	0.416917
140	140	2	0.368684	4.859178	1.682363
160	160	3	0.385485	4.351338	0.419667
180	180	2	0.400718	3.945386	0.959228
200	200	5	0.414665	3.612344	0.533058
220	220	4	0.427536	3.33348	0.133269
240	240	5	0.43949	3.096096	1.170781
260	260	3	0.450653	2.891253	0.00409
280	280	1	0.461126	2.712458	1.081127
300	300	2	0.47099	2.554872	0.120508
320	320	0	0.480313	2.414811	2.414811
340	340	2	0.489153	2.289411	0.036585
43741	43741	128	0.995196	131.0651	0.07168
	More	0		**Crit. Value**	**24.63202**

Fig. A.11: Example of the Chi-square test as performed in Excel.

Fig. A.12: Packer – MTBF Distribution.

The Weibull (0.33, 278.4) has passed the chi-square test with a significance of 5% and 31 degrees of freedom.

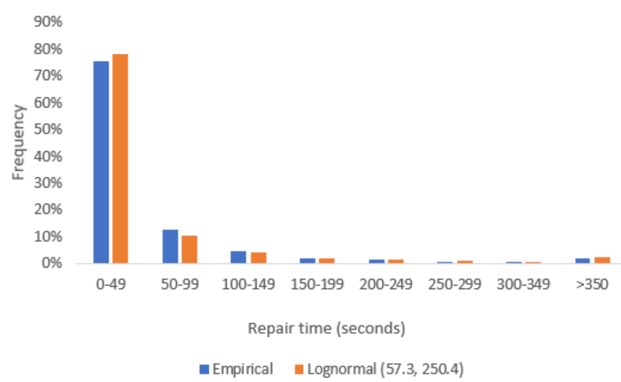

Fig. A.13: Packer – MTTR Distribution.

The Lognormal (57.3, 8) has passed the chi-square test with a significance of 5% and 31 degrees of freedom.

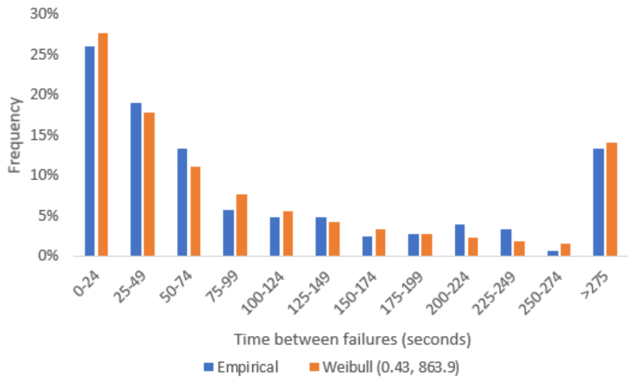

Fig. A.14: Palletizer – MTBF Distribution.

The Weibull (0.43, 863.9) has passed the chi-square test with a significance of 5% and 17 degrees of freedom.

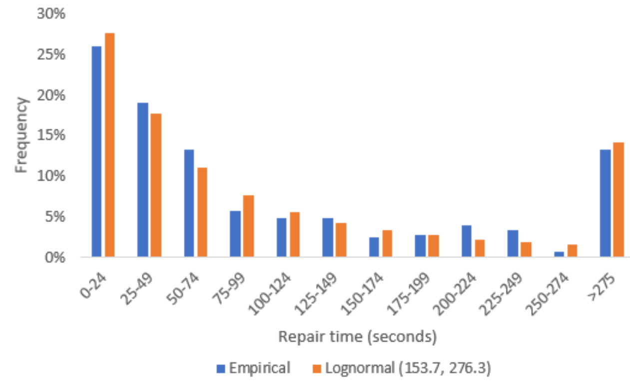

Fig. A.15: Palletizer – MTTR Distribution.

The Lognormal (153.7, 276.3) has passed the chi-square test with a significance of 5% and 18 degrees of freedom.

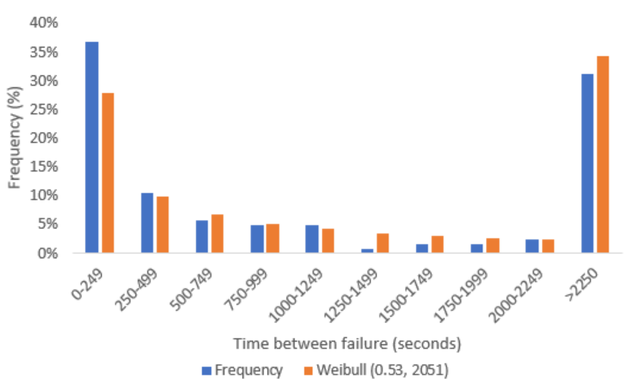

Fig. A.16: Sheet Applicator – MTBF Distribution.

The Weibull (0.53, 2051) has passed the chi-square test with a significance of 5% and 13 degrees of freedom.

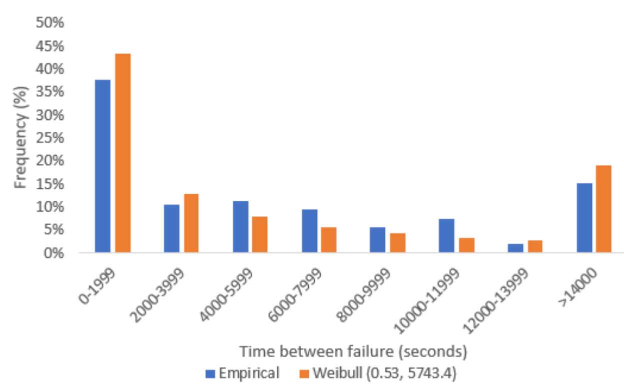

Fig. A.17: Sheet Applicator (good material) – MTBF Distribution.

The Weibull (0.53, 5743.4) has passed the chi-square test with a significance of 5% and 11 degrees of freedom.

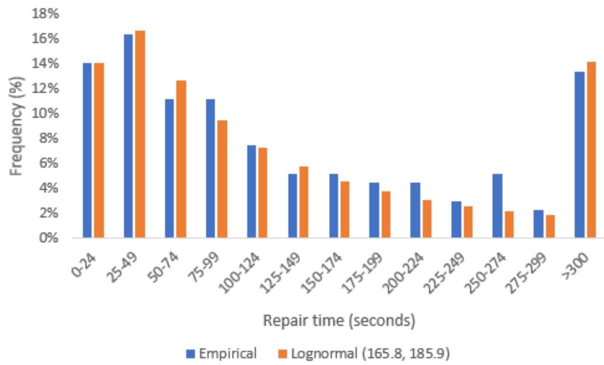

Fig. A.18: Sheet Applicator – MTTR Distribution

The Lognormal (165.8, 185.9) has passed the chi-square test with a significance of 5% and 13 degrees of freedom.

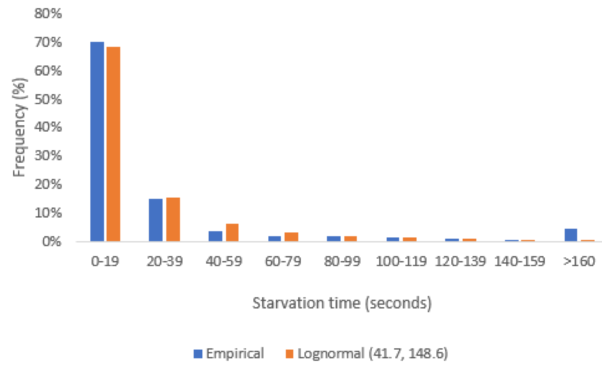

Fig. A.19: Line 41 – MST Distribution.

The Lognormal (41.7, 148.6) has **not** passed the chi-square test with a significance of 5% and 81 degrees of freedom.

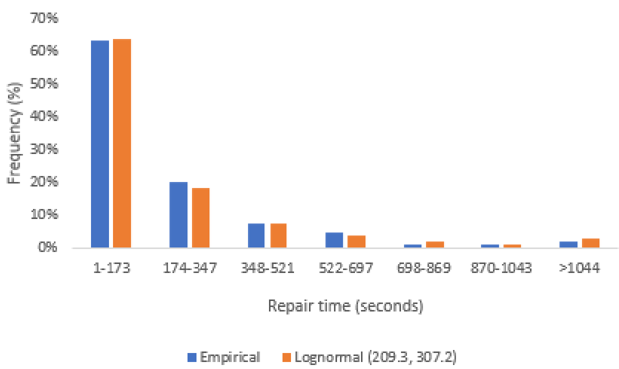

Fig. A.20: Shrink wrapper – MTTR Distribution.

The Lognormal (209.3, 307.2) has passed the chi-square test with a significance of 5% and 13 degrees of freedom.

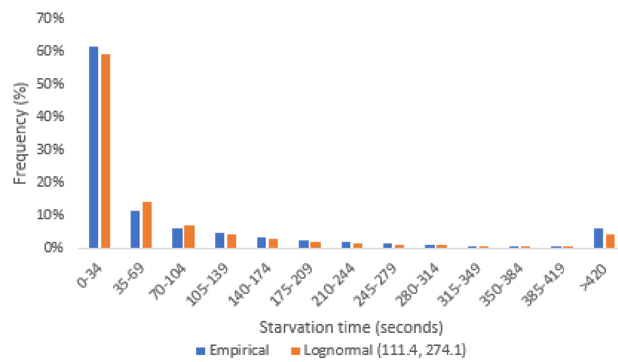

Fig. A.21: Line 42 – MST Distribution.

The Lognormal (111.4, 274.1) has **not** passed the chi-square test with a significance of 5% and 51 degrees of freedom.

Appendix 9: Experimental Factor: Shrink Wrapper

Finally, several test have been executed regarding the speed of the shrink wrapper. The experiment contains three stage: current scenario, a speed boost of 5%, and a speed boost of 10%. As discussed in Section 1.4, this have been excluded by the scope of this research study. However, the effect of speed modification on the line performance still have been analyzed as it is relevant for Heineken. Moreover, it is requested by the management.

The same experiment was performed during the adjustment that no failures occurred at the shrink wrapper. Now it can be proofed whether the speed or failure rate is the most restrictive variable of the shrink wrapper.

Results and Interpretation: Shrink Wrapper Modifications

Table A.3 shows a large improvement of the current system's throughput as the speed of the shrink wrapper increases. Moreover, the blockage ratios of the palletizers reduce and starvation ratio of the shrink wrapper increases (see Table A.4). This same modification have been tested in a modified system where no failure occur at this machine. The results of Table A.5 show that the effect of an increased speed is much smaller on the overall throughput. Hence, it can be concluded that one should focus on the failure ratio instead of a modification in processing speed.

Table A.3: Throughput – Experiment: speed modification (confidential).

Scenario	Throughput 41	Throughput 42	Throughput 43
Current			
+5% Speed			
+10% Speed			

Table A.4: Blockage and starvation – Experiment: speed modification.

Scenario	Blockage Palletizer 41	Blockage Palletizer 42	Blockage Palletizer 43	Starvation Shrink Wrapper
Current	4.8%	9.2%	0.0%	8.0%
+5% Speed	2.8%	5.8%	0.0%	11.5%
+10% Speed	1.9%	3.4%	0.0%	14.8%

Table A.5: Throughput – Experiment: no failures and speed modification (confidential).

Scenario	Throughput 41	Throughput 42	Throughput 43
Current			
+5% Speed			
+10% Speed			

Appendix 10: Cost Savings per Modification

This appendix presents the (non-)cash savings and implementation costs per modification. In addition to the calculation of the alternative solution, it is also relevant to determine these modifications individually as this provides additional insights for Heineken. The calculations used are the same as the computations performed in Section 5. Table A.6 presents the non-cash savings and cash savings per modification for lines 41 and 42.

Table A.6: Non-cash savings and cash savings per modification and line (confidential).

Line	Modification	Increased OPI	Non-cash savings	Cash savings
41	Dynamic	+ 0.24%		
	Good material	+ 0.79%		
	SLACK rule	+ 0.42%		
42	Dynamic	+ 0.24%		
	Good material	+ 0.79%		
	SLACK rule	+ 0.42%		

The direct labor costs per implementation are calculated by multiplying the salary costs (i.e., X per hour) by the time required to implement a certain modification. Table A.7 shows the results of these costs.

Table A.7: Implementation costs per modification (confidential).

Modification	Duration	Costs
Dynamic	4 hours	
Good material	4 hours	
SLACK rule	16 hours	