Optimizing a production line

A simulation study

Bachelor Thesis Industrial Engineering & Management

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Preface

This report is the result of the bachelor thesis that I have conducted for my bachelor Industrial Engineering & Management at the University of Twente. I have conducted my bachelor thesis at Company X. At Company X, I have made an analysis on the new to be built production line by means of a simulation model to detect possible bottlenecks and to come up with methods to eliminate those bottlenecks.

I would like to thank several people that have assisted me during the creation of my bachelor thesis. At first, I would like to thank my supervisor at Company X, for his pleasant guidance and his useful feedback. Even though he was very busy, he always created a gap in his agenda to help me out. Second, I would like to thank all the other employees at Company X that made sure that I had a good time working there and who gave very useful input for my bachelor thesis.

Next to that, I would like to thank my first supervisor at the University of Twente, Matthieu van der Heijden, for his help during my bachelor thesis. Matthieu always provided very critical and very useful feedback, of which I have learned a lot. I would also like to thank Sandor Löwik and Hans Heerkens, who taught me a lot during the preparation of my bachelor thesis. Besides that, I would like to thank my second supervisor at the University of Twente, Leo van der Wegen, for his useful feedback on my bachelor thesis.

Finally, I would like to thank Tim van Benthem, a very good friend and my buddy in reviewing our bachelor theses. Tim always came up with very useful feedback and had a lot of creative ideas to improve my bachelor thesis.

Mark Bergman, 2018

Summary

Introduction
Company X produces products varying from 150ml bottles to 1000L boxes. Both the current 5L production line and 10L production line have a throughput of around 30 cans per minute. This amount is too low, implying that the operational costs per can are too high. In order to decrease the operational costs, those production lines will be combined into one production line with new workstations, which will increase the throughput a lot.

I am asked to create a simulation model of the new production line and my assignment is to "maximize the throughput of the combined 5L and 10L production line while taking into account the use of resources".

Production line optimization techniques
To maximize the throughput while taking into account the use of resources, I first detected the bottleneck in the production line by looking at the lowest effective processing speed; the other bottleneck detection method that I used provided incorrect results. After that, I have performed one iteration of the Theory of Constraints, which focusses on the elimination of production line bottlenecks. To eliminate the bottleneck, I used different production line optimization techniques, namely: buffering techniques, the V-curve principle and the extended version of the V-curve principle.

Experiments with the simulation model
After having acquired a lot of information about the production line and production line optimization techniques, I have created a simulation model with which I performed a lot of experiments. I first detected the bottleneck, performed experiments with production line optimization techniques and I conducted additional experiments regarding the placement of boxes on the buffer of the box erector, the processing speed of the depalletizer and the buffer size in front of and behind the bottleneck.

Conclusions and recommendations
The experiments with the simulation model showed that the filler capper is the bottleneck, using the second bottleneck detection method, for both production schemes. However, only a buffer of 210 5L cans in front of the filler capper and 90 5L cans behind the filler capper will increase the throughput. As this buffer size is not feasible given the costs and space, I recommend Company X to not use any production line optimization technique. This will lead to an average throughput of either about 70 5L cans per minute or 45 5L cans per minute and a corresponding OEE of 26.5% or 31.5%.

Next to that, Company X should purchase the box erector that was expected to be purchased. This workstation will double the average time between the filling of the buffer of the box erector to 10 minutes, which will create even better working conditions for the operators.

Also, the depalletizer is not the bottleneck, which is contradictory to the first bottleneck detection method. Increasing the processing speed of the depalletizer did not increase the average throughput of the production line, as the filler capper could not handle the increased supply from the depalletizer and the sleever. Therefore, I advise Company X to not purchase a depalletizer with a processing speed higher than a processing speed of 100 5L cans per minute or 60 10L cans per minute.

Finally, I recommend Company X to update my simulation model if the production line does not perform as expected or when the production line does not seem to be balanced. The simulation model should then be updated after having collected half a year of data when the start-up phase of the production line is over. A more accurate simulation model might provide useful insights into the production line, which might help to increase the performance of the production line. When Company X is not able to work with the simulation model, I advise them to update and to further develop the deterministic model of the production line, which might also provide useful insights into the production line.

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Reader's guide

This reader's guide is created to give the reader a better understanding of the structure of my bachelor thesis. I will first give a short overview of the different chapters in my bachelor thesis, which is presented below.

Chapter 1 Introduction covers the introduction to my bachelor assignment. This chapter covers, amongst others, an introduction to my assignment, the problem statement, the problem approach and the research design.

Chapter 2 Information about the production line covers information about the production line in terms of the products that will be produced, the workstations in the production line, the batch changing process, and the KPIs that will be optimized in this bachelor thesis.

Chapter 3 Information about production line optimization techniques covers information about production line optimization techniques. It covers a method to detect a bottleneck in the production line, theory on the effects of a standstill of a bottleneck, a systematic literature review about production line optimization methodologies, and theory on production line optimization techniques.

Chapter 4 Conceptual model of the production line covers the conceptual model of the production line, that is used to create a simulation model of the production line. It covers, amongst others, simplifications made in the simulation model, input variables for the simulation model, and output variables of the simulation model.

Chapter 5 Implementation, verification and validation of the simulation model elaborates on the implementation of the conceptual model into a simulation model and a verification and validation of the simulation model.

Chapter 6 Experiments with the simulation model covers the experiments with the simulation model. At first, a statistical preparation of the experiments and an introduction to the experiments are presented. After that, a lot of experiments are conducted with the simulation model.

Chapter 7 Deterministic model of the production line covers the deterministic model of the production line. At first, the model is explained and after that, the outcomes are presented. Finally, the outcomes of the deterministic model are compared to the outcomes of the simulation model.

Chapter 8 Conclusion, recommendations and discussion covers the conclusion on my experiments conducted in chapter 6. Next to that, I have made recommendations to Company X in terms of production line parametrization, data collection, and regarding the continuation of my bachelor thesis and models. I will also critically look at things that could improve the quality of my bachelor thesis and I will discuss the effects of the simplifications that I have made in my simulation model.

Each chapter is structured in the same way. At first, a short introduction to the chapter is given, after which the structure of the chapter (in terms of sections) is outlined by means of a bullet list. This will increase the structure of my bachelor thesis and with that also the readability of my bachelor thesis.

I wish you a lot of pleasure when reading my bachelor thesis.

Mark Bergman, 2018

Definitions

In this bachelor thesis, I might use some terms that have other definitions in other contexts. To avoid that the reader misunderstands the terms that I have used in my bachelor thesis, I have created a list of definitions below.

Workstation	Another word for machine. I use the term workstation as the filler capper consists of two machines, the filler and the capper, but can be seen as one machine. Therefore, I use the term workstation to avoid uncertainties.
Processing speed	The number of products that can be processed in a certain time period. In this case, the processing speed is measured in terms of the number of products that can be processed per minute.
Workstation cycle time	The time spent in a workstation by a product. The workstation cycle time is much longer than the processing time of a product in a workstation. The product often stays in the workstation, while the product behind that product is processed.
Batch size	The number of products that are produced in one production run. In my bachelor assignment, either 2000 5L cans or 1000 10L cans form one batch.
Workstation processing size	The maximum number of products that are simultaneously in the workstation. When a workstation has a processing size of 43, such as the filler capper, 43 cans are processed in parallel or in series and are thus in the workstation at the same time.

1 Introduction

In this chapter, I will give an introduction to my bachelor assignment by introducing Company X, presenting my assignment and my problem approach and research design. This chapter is structured as follows:

- Section 1.1 gives an introduction to Company X.
- Section 1.2 describes the motivation for the research.
- Section 1.3 presents the assignment description.
- Section 1.4 presents the problem statement.
- Section 1.5 gives an introduction to the problem approach.
- Section 1.6 presents the problem approach and the research design.

1.1 Introduction to Company X

Because of confidentiality agreements, information about the type of products that are produced by Company X and any information that could be linked to the company is not presented.

Company X produces products varying from 150ml bottles to 1000L boxes. The company particularly excels in terms of automation, as almost every production line is fully automated, which results in having a small number of operators working at each production line. Most of the production lines only need one operator who is checking the products produced on the line and who performs maintenance activities on the machines. At the end of the production line, there is an automatic guided vehicle that transports the final product from each production line, a pallet with boxes containing the product, to the wrapping machine.

1.2 Motivation for the research

During the last few years, Company X had the task of reducing the operational costs. Many small projects have been conducted to reduce the operational costs, only those reductions were not large enough. Right now, Company X is conducting a big project to reduce the operational costs heavily by combining the 5L and the 10L production line into a line with almost a double throughput. As this project asks for an enormous investment, I am asked to advise Company X on how to maximize the throughput of this production line, while taking into account the use of resources, which is the goal of my research. A more in-depth explanation of my assignment can be found in Section 1.3.

1.3 Assignment description

My assignment will be conducted in the Filling Department, which is part of the Operations section in the Value Chain of Company X. This assignment is created to increase the throughput of 5L and 10L cans from the combined production line.

Both the current 5L production line and 10L production line have a throughput of around 30 cans per minute. This amount is too low, therefore the operational costs per can are too high. In order to decrease the operational costs, those production lines will be combined into one production line containing workstations with a much higher processing speed.

The assignment that Company X gave me is described as follows:

“Maximize the throughput of the combined 5L and 10L production line while taking into account the use of resources”

The primary goal is thus to maximize the throughput of the production line, but I have to do this by taking into account the use of resources. Just maximizing the throughput will be very easy, as I will use the maximum production speed of the workstations and place huge buffers between the workstations. With the constraint of taking the use of resources, I should decrease the buffers and the production speed as much as possible when this has little effect on the throughput. Resources that can be thought of in this assignment are, buffers, space and money.

1.4 Problem statement

The action problem (Heerkens & Van Winden, 2012, p. 22) regarding this project is that the combined throughput from the 5L can production line and the 10L can production line from Company X is too low. Both production lines have a throughput of around 30 cans per minute.

Company X wants a production line, that can be used for both the 5L cans and 10L cans, that has the highest possible throughput that can be acquired with the workstations that will be bought. So, in terms of a reality and a norm (Heerkens & Van Winden, 2012, p. 23), the reality is that the 5L can throughput is around 30 cans per minute and the norm is the highest possible throughput of 5L cans per minute that can be acquired with the workstations that will be bought. Regarding the 10L can throughput, the reality is that the throughput is around 30 cans per minute and the norm is the highest possible throughput of 10L cans per minute that can be acquired with the workstations that will be bought.

Company X will purchase workstations which are all able to produce at least 100 5L cans or 60 10L cans per minute. However, just purchasing new workstations will not solve the action problem completely. The complete production line has to be designed. Company X already received a part of the suggested design (from the supplier of the workstations) for the production line. The project team that is responsible for the project of building the combined production line will finish this design. After the production line is designed, the production line has to be configured in such a way that the throughput will be maximized. With this configuration, the parametrization of the workstations in terms of production speed and the parametrization of the buffer locations is meant.

As described in Section 1.3, I am asked to optimize the production line, in terms of maximizing the throughput while taking into account the use of resources. In order to answer this question, I will need to answer, amongst others, the following questions:

1. **What should be the production speeds of the workstations?**
2. **What is the effect of a certain buffer size between certain workstations?**

I created a problem approach to solve the problem. The introduction to my problem approach is presented in Section 1.5.

1.5 Introduction to problem approach

The problem approach is the second phase of the Managerial Problem Solving Method (Heerkens & Van Winden, 2012, p. 39). In this phase, a design is made for the solution process, in this case, an optimization of the production line. At first, I will describe my motivation for conducting a simulation study. After that, an overview of the problem approach will be presented. The problem approach and the corresponding research design will be further explained in Section 1.6.

1.5.1 Motivation for conducting a simulation study

To solve the action problem, I will conduct a simulation study in Plant Simulation. I have chosen to conduct a simulation study for the following reasons:

1. With a simulation model, there is a visual representation of the future production line, in which the product flow through the production line is visible. This is more convincing than difficult formulas that arise from queueing theory (Robinson, 2014, p. 15).
2. With a simulation study, you can use a lot of KPIs, while this is much harder with queueing theory.
3. Assumptions about for example distributions can more easily be made in a simulation model than when using queueing theory (Robinson, 2014, p. 15).
4. The level of detail can be much higher in a simulation model than a queueing model.

1.5.2 Overview of my solution process

To create a clearly structured solution process, the solution process is divided into 6 different phases. In this section, I will further elaborate upon these phases. These phases are:

Phase 1: Collect information about the combined production line

In this phase, I will collect information about the combined production line. I will find out what products will be produced on this production line and which workstations are to be included in this production line and what main activities are performed at each workstation. After that, I will find out which KPIs will be used to determine the performance of a production line configuration. Next to that, I will conduct an interview regarding which KPIs I have to optimize the production line.

Phase 2: Collect information about production line optimization techniques

In this phase, I will first collect information on how I can detect the bottleneck in the production line and what the effects of a standstill of the bottleneck are. After that, I will conduct a systematic literature review about production line optimization methodologies, in terms of theory explanation and case studies. After that, I will search for production line optimization techniques, that can be used to support the production line optimization methodologies, in textbooks. At the end of this chapter, I will describe which production line optimization methodologies and production line optimization techniques I will use to optimize the production line.

Phase 3: Create a conceptual model of the combined production line

In this phase, I will build a conceptual model of the combined production line. I will first look for simplifications that can be made in the simulation model, for which I will ask for confirmation from the management team. After that, I will determine which input and output variables I have to use in my simulation model, by integrating the information acquired in Phase 1 and by conducting interviews with the management team and the project team.

Phase 4: Implement, verify and validate the simulation model

In this phase, I will implement my conceptual model in a simulation model. After that, I will verify and validate my simulation model, by using the techniques described by Robinson (2014).

Phase 5: Conduct experiments with production line optimization techniques

In this phase, I will conduct experiments with the chosen production line optimization techniques. Before I can experiment, I have to find out which preparations have to be made. After that, I will create a list of experiments that will be conducted. Next, I will conduct the experiments, including sensitivity analyses, and describe the outcome of each experiment.

Phase 6: Advise a production line configuration to Company X

In this phase, I will first conclude on the experiments conducted in Phase 5. After that, I will present recommendations to Company X in terms of production line parametrization. Finally, I will have a critical discussion on my simulation model.

1.6 Problem approach and research design

In this section, I will describe the problem approach that I will follow in order to be able to propose a solution to Company X. I will, for each phase, present the main the research question followed by sub-questions that need to be answered in order to answer the main research question. After that, a short explanation of the research design for each sub-question is presented.

1.6.1 Phase 1: Collect information about the combined production line

For this phase, I have created the main research question, supported by five sub-questions. These questions are answered in Chapter 2.

1) What will the future production line look like and what are my degrees of freedom regarding production line optimization?

a) Which products will be produced on this production line?
b) Which workstations are part of this production line and what are the main activities performed on each workstation?
c) What does the batch changing process look like?
d) What KPIs are currently used to determine the performance of a production line configuration?
e) Regarding which KPIs do I have to optimize the production line?

First, it is important to understand the future production line. Information about the products that will be produced, which workstations are part of the production line and what activities are performed on each workstation, and what the batch changing process looks like will help to understand the production line. These three sub-questions are answered by conducting interviews with the production line operators, as they have a lot of experience with the current 5L and 10L production line. It is also important to acquire information about how Company X measures the performance of a production line and regarding which KPIs I have to optimize the production line. These two sub-questions are answered by conducting an interview with the management team.

1.6.2 Phase 2: Collect information about production line optimization techniques

For this phase, I have created the main research question, supported by five sub-questions. These questions are answered in Chapter 3.

2) How can I optimize the production line of Company X?

a) How can I detect the bottleneck in the production line?
b) What are the effects when the bottleneck has a standstill?
c) Which production line optimization methodologies exist in the literature and how are they applied in practice?
d) Which production line optimization techniques can I use to optimize the production line?
e) Which production line optimization methodologies and techniques will be tested in a simulation study?

Second, it is important to understand how a production line can be optimized. At first, it is important to know how to detect a bottleneck in a production line and what the effects of a bottleneck standstill are. Both sub-questions are answered by conducting a literature study (Kikolski, 2016). After that, it is important to learn about production line optimization methodologies and production line optimization techniques that can be used to optimize the production line. Those questions are answered by conducting a systematic literature review and a literature review respectively. The final sub-question is very important, as this sets the basis for the experiments that will be conducted in Phase 5. This sub-question is answered by conducting a discussion session with the management team, as I want to shape my advice according to their preferences.

1.6.3 Phase 3: Create a conceptual model of the combined production line

For this phase, I have created the main research question, supported by three sub-questions. These questions are answered in Chapter 4.

3) What does the conceptual model of the combined production line look like?

a) What simplifications can be made in this simulation model?
b) What are the input data for the simulation model?
c) What are the output variables of the simulation model?

Third, it is important to create a conceptual model of the production line as this can be used to create a simulation model of the production line. At first, it is important to look for simplifications that can be made in the simulation model. This question is answered by conducting interviews with the operators and the management team, in which I have proposed simplifications and asked for confirmation to use those simplifications. Next to that, input variables should be created for the simulation model. This is done by using the information received in Phase 1 and by conducting additional interviews with the operators and the management team about data of the production line. Finally, it is important to create output variables on which the production line performance can be judged. These output variables are created by using the information acquired in Phase 1.

1.6.4 Phase 4: Implement, verify and validate the simulation model

For this phase, I have created the main research question, supported by two sub-questions. These questions are answered in Chapter 5.

4) How can I implement, verify and validate the simulation model?

a) How can I implement the simulation model?
b) How can I verify and validate and the simulation model?

Fourth, the production line has to be implemented in the simulation model, and the simulation model has to be verified and validated. The first sub-question is answered by creating a simulation model using the information acquired in Phase 3. After the simulation model is created, it is very important to verify and validate the simulation model as the simulation model should be accurate. This sub-question is answered by conducting a literature study (Robinson, 2014).

1.6.5 Phase 5: Conduct experiments with production line optimization techniques

For this phase, I have created the main research question, supported by three sub-questions. These questions are answered in Chapter 6.

5) Which experiments will be conducted in my simulation study?

a) Which preparations have to be made before experimenting?
b) Which experiments, including sensitivity analyses, will be conducted with a simulation study?
c) What are the results of each experiment?

Fifth, experiments should be conducted to optimize the production line. Before conducting experiments, it is very important to statistically prepare the experiments to make sure that the conclusions that will be made are statistically correct. This question is answered by conducting a literature study (Robinson, 2014). After that, the experiments that will be conducted have to be created. This sub-question is answered by using the information acquired in Phase 3. After determining which experiments will be performed, the results of each experiment have to be presented.

1.6.6 Phase 6: Advise a production line configuration to Company X

For this phase, I have created the main research question, supported by three sub-questions. The first question is answered in Chapter 7, the second question is answered in Chapter 8 and the third question is answered in Chapter 9.

6) Which configuration should be used by Company X?

a) What conclusions can be drawn from the experiments?
b) Which production line parametrization do I recommend to Company X?
c) Which limitations might have influenced the accuracy of my simulation model?

Finally, a production line configuration should be advised to Company X. First, conclusions have to be drawn from the experiments. After that, I have to recommend a production line parametrization to Company X, based on the conclusions drawn from the experiments. At last, it is important to critically discuss the simulation model, as there might be some limitations that might have influenced the accuracy of my simulation model.

Now that the problem approach and research design are presented, information about the production line can be collected, which is presented in Chapter 2. In this chapter, the products that will be produced on the production line, the workstations in the production line and the product routes, the batch changing process, the KPIs that Company X currently uses to determine production line performance, and the KPIs that will be optimized in this simulation study are discussed.

2 Information about the production line

In this chapter, I will present more general information about the production line. I will answer the following research question in this chapter: “What will the future production line look like and what are my degrees of freedom regarding production line optimization?”. This chapter is structured as follows:

- Section 2.1 describes the products to be produced on the production line.
- Section 2.2 describes the workstations in the production line and the product routes.
- Section 2.3 describes the batch changing process.
- Section 2.4 describes the KPIs that determine production line performance.
- Section 2.5 describes the KPIs that will be optimized in this simulation study.

2.1 Products to be produced on the production line

This section answers the question: “Which products will be produced on this production line?”. There are two types of products that are to be produced on the production line: the 5L cans and 10L cans, which are described below. In Section 2.1.3, I have created different product groups.

2.1.1 5L cans

There are roughly 200 different SKUs that are produced on the current 5L production line. Further details about the SKUs are not presented because of confidentiality agreements. The 5L cans are placed into a box, which is labeled afterwards. The cans contain either a sleeve or a label.

2.1.2 10L cans

There are roughly 80 different SKUs that are produced on the current 10L production line. Further details about the SKUs are not presented because of confidentiality agreements. The 10L cans contain only a sleeve, only a label or both a sleeve and a label. The 10L cans are not placed into boxes.

2.1.3 Product groups

By summarizing Sections 2.1.1 and 2.1.2, I have created five different product groups. Those product groups are presented in Table 2.1 in which the characteristics of each group are described. These product groups are created based on the way in which they are packed. No distinction is made between the type of product.

Product group	Type of product	Sleeve?	Label on can?	Packed in a box?	Label on box?
5L_Type1	5L	YES	NO	YES	YES
5L_Type2	5L	NO	YES	YES	YES
10L_Type1	10L	YES	NO	NO	NO
10L_Type2	10L	NO	YES	NO	NO
10L_Type3	10L	YES	YES	NO	NO

Table 2.1 | Product groups

2.2 Workstations in the production line

This section answers the question: “Which workstations are part of this production line and what are the main activities performed on each workstation?”. First, all the different workstations are described and after that, different routes through the workstations are presented.

2.2.1 List of workstations in the production line

There are 10 workstations that will be part of the production line. The production process starts at the depalletizer and ends at the palletizer. All workstations are completely automated, meaning that the operator only has to monitor if the process is going well and repair the workstations if needed. All workstations in the production line are listed below. Next to that, the layout of the production line including these workstations is presented in Figure 4.2 in Section 4.2.6.

1. **Depalletizer:** At the depalletizer, all cans that arrive on a pallet are placed onto the production line. The depalletizer unpacks a pallet layer by layer. Each layer consists of either 54 5L cans or 30 10L cans.
2. **Sleever:** At the sleever, the can will be provided with a sleeve, which is pulled over the can. The sleeves are applied in series, meaning that the application of the sleeve to the first can begins slightly earlier than the application of the sleeve to the second can. The sleever has a processing size of either 20 5L cans or 16 10L cans.
3. **Filler/capper:** The filler and the capper are two machines that are synchronized to each other and can, therefore, be seen as one workstation. In the filler, 43 cans (5L or 10L) are simultaneously filled with the product. After that, the capper puts a cap on the can.
4. **Labeler:** At the labeler, a label is placed onto the can. One can is provided with a label at the time, meaning that the labeler has a processing size of 1 can.
5. **Box erector:** The box erector delivers the boxes that are used to pack the cans with the product. In front of the box erector, there is a stock of folded up boxes. These boxes are unfolded in batches of 4 by the box erector, which makes them ready to be used by the packing machine.
6. **Packing machine:** The packing machine picks up ten cans at a time and places them into five boxes that are provided by the box erector. There is a maximum speed at the packing machine, to make sure that the cans are placed into the box correctly.
7. **Tape machine:** The tape machine seals the boxes by placing a stroke of tape at the top of the box and at the bottom of the box. This makes sure that the box is closed correctly. One box is foreseen by a stroke of tape at the time, meaning that the tape machine has a processing size of 1 box.
8. **Box labeler:** The box labeler places a label on the box. The front of the box will always contain a label; for some orders, an additional label on the back of the box is required. One box is foreseen by a label at the time, meaning that the box labeler has a processing size of 1 box.
9. **Track and trace labeler:** The track and trace labeler prints a track and trace code on the can or box. This track and trace code contains the product number, the batch number, the date and time of filling. With this, the product can be linked to the operator who 'created' the product. If there are some errors in the products, this can be fed back to the operator, such that he can improve himself by learning from mistakes. This will make sure that he will not make the same mistake anymore. One box is provided with a track and trace code at the time, meaning that the track and trace labeler has a processing size of 1 can or box.
10. **Palletizer:** At the palletizer, all boxes with cans that are filled with the product, are placed on a pallet. The boxes are pushed in the position of a pallet layer. If a pallet layer is created, then this layer is pushed away and a new layer can be filled. The layers are then stacked by bringing a layer down, such that the next layer can be pushed on it.

After the palletizer, the pallets are transported to the wrapper by a transfer car, but this process is out of the scope of my assignment. Therefore, the palletizer is assumed to be the final workstation in the production line and the pallet with boxes is assumed to be the end product.

2.2.2 Different routes for different products

As mentioned in Section 2.1.3, there are different product groups. Each product group has its own route on the production line, meaning that some product groups are processed ("YES") or not ("NO") on certain workstations. These different routes for the product groups are presented in Table 2.2 below.

	5L_Type1	5L_Type2	10L_Type1	10L_Type2	10L_Type3
Depalletizer	YES	YES	YES	YES	YES
Sleever	YES	NO	YES	NO	YES
Filler/capper	YES	YES	YES	YES	YES
Labeler	NO	YES	NO	YES	YES
Box erector	YES	YES	NO	NO	NO
Packing machine	YES	YES	NO	NO	NO
Tape machine	YES	YES	NO	NO	NO
Box labeler	YES	YES	NO	NO	NO
Track and trace labeler	YES	YES	YES	YES	YES
Palletizer	YES	YES	YES	YES	YES

Table 2.2 | Routes for different product groups

As can be seen in Table 2.2, some product groups pass the sleever or the labeler. For the 5L cans, there is a switch at the sleever, which can either activate the sleever and simultaneously deactivate the labeler. For the 10L cans, there is a switch at both the sleever and the labeler, which can activate and deactivate the corresponding workstation.

2.3 Batch changing process

This section answers the question: "What does the batch changing process look like?". I will elaborate on what the batch changing process looks like, what operators have to do and the batch changing time.

At the end of a batch, the production line has to be cleaned. The filler capper is emptied and after that, the buffer tank is cleaned and the remaining product in the pipes is flushed away into a waste box. Next to that, the complete production line has to be configured according to the product that has to be produced. The operator has to change, amongst others, the labels of the labeler and the box labeler, the roll of tape of the tape machine, the sleeves and the pressure of the filler capper. All the materials are replaced by the operator himself. Also, the operator receives a checklist with, amongst others, the codes of the labels and the sleeves, which have to be checked. No activities are performed on the depalletizer, the packing machine and the palletizer. Therefore, the depalletizer places the cans for the next batch on the line during the batch changing process, which will save a lot of time.

After everything is configured in the right way, the operator has to take a sample of the product to determine if the product quality and the concentration of the product are good. Next to that, the operator should check whether the labels are correctly placed onto the cans and boxes. If this sample is approved by the operator, the new batch can be produced.

There is no fixed time for the batch changing process; the required cleaning time is only dependent on the type of product that was produced in this batch. The cleaning process of some products can be finished very fast; the cleaning process of other products takes much longer to finish.

During the cleaning time, the operator configures the production line in the correct way. The cleaning time takes longer than the configuration time; therefore, the cleaning time is the bottleneck. This cleaning time cannot easily be reduced, however.

In Appendix 1, a detailed time schedule of a batch changing process is presented. I observed a batch changing process of the current 5L production line on a random day in which two operators performed the batch change.

2.4 KPIs that determine production line performance

This section answers the question: "What KPIs are currently used to determine the performance of a production line configuration?". I will elaborate on how Company X used to determine production line performance and how this determination has changed over time.

In the past, Company X used one measurement to determine production line performance: Overall Equipment Effectiveness (OEE). One part of the OEE includes the average throughput, which will be the first objective of my simulation study. I will first elaborate on the average throughput and after that, I will elaborate on the OEE. Next to that, I will elaborate on the use of resources, as this also influences production line performance.

2.4.1 Average Throughput

The average throughput is measured in terms of cans per minute, in which batch changing times are excluded. As the goal of my assignment is to "maximize the throughput of the combined 5L and 10L production line while taking into account the use of resources", the average throughput is my first objective.

2.4.2 Overall Equipment Effectiveness (OEE)

The OEE includes availability, performance, and quality. The formula that is used to determine the OEE is:

$$\text{OEE } (\%) = \text{availability } (\%) \times \text{performance } (\%) \times \text{quality } (\%)$$

The availability is defined as follows: "a comparison of the potential operating time with actual time the equipment is producing products". The availability can be calculated by dividing the running time by the net operating time. The net operating time is the time that is scheduled for the batches. The running time is the time that the production line is operational, so it excludes workstation downtimes.

The performance is defined as follows: "a comparison of the actual output and what the equipment can produce.". The performance can be calculated by dividing the actual output by the target output. The target output is determined is the target number of products that should be produced per minute and the actual output is the actual number of products that are produced per minute.

The quality is defined as follows: "a comparison of the number of products produced and the number of products that meet the customer's expectation.". The quality can be calculated by dividing the good output by the actual output. The actual output is the actual number of products produced and the good output is the number of products that are produced that meet the customer's expectation.

Company X used to determine the availability by looking at the availability of the bottleneck in the production line. The bottleneck had a lot of minor standstills, which influenced its availability, but did not influence the actual throughput, as buffers were created to deal with these minor standstills. Therefore, Company X now determines the availability by looking at the availability of the palletizer, which is the last workstation in the production line. This workstation measures the actual throughput of the production line much better as minor standstills from this workstation do influence availability and the actual throughput, as no buffers can be placed after the last workstation in the production line.

Company X used to determine the performance by setting a target throughput for each batch, in terms of products to be produced per minute, and by calculating the actual number of products that are produced per minute.

Company X did not determine the quality of the of the products, as they did not track the number of products that were thrown away during the production process.

2.4.3 The use of resources
Company X also takes into account the use of resources, for example the use of buffers, space, money and the number of operators. These resources have to be minimized, as this is stated in the goal of my assignment, which is “maximize the throughput of the combined 5L and 10L production line while taking into account the use of resources”.

2.5 Conclusion: KPIs that will be optimized
This section answers the question: “Regarding which KPIs do I have to optimize the production line?”. I will elaborate on how I will optimize the production line and I will describe other measurements that have to be taken into account when determining the performance of a production line.

2.5.1 Average Throughput
My first objective is to maximize the average throughput, as this is the goal of my assignment. The average throughput will be determined by dividing the total number of cans produced by the total time of producing, which excludes batch changing processes.

2.5.2 Overall Equipment Effectiveness
My second objective is to maximize the OEE of the production line. The availability will be determined by the average availability of the workstations in the production line. During a 10L production process, the availability of the box erector, the packing machine and the tape machine will not be taken into account. The performance will also be calculated at the end of the simulation run. I will not model product defects, so I will assume that the quality of the products equals 100%.

2.5.3 Use of resources
After having maximized the average throughput and after that OEE, I will look at the use of resources. If a buffer will be placed in the production line, I will determine the minimum capacity at which it can increase the average throughput. So, if the average throughput is the same with a buffer capacity of 50 cans as with buffer capacity of 75 cans, I will use a buffer capacity of 50 cans.

Another thing that I will look at is the average time between two consecutive fillings of the buffer of the box erector, which is performed by the operator. I will minimize this buffer capacity as much as possible, as it saves space and money, to such a level that it is feasible for the operators.

Now that the information about the production line is collected, information about production line optimization techniques can be acquired. This is discussed in Chapter 3.

3 Information about production line optimization techniques

In this chapter, I will elaborate on production line optimization techniques. I will answer the following research question in this chapter: "How can I optimize the production line of Company X?"**.** This chapter is structured as follows:

- Section 3.1 describes how a bottleneck can be detected in a production line.
- Section 3.2 describes the effects of a standstill of the bottleneck.
- Section 3.3 describes production line optimization methodologies.
- Section 3.4 describes production line optimization techniques.
- Section 3.5 describes the choices that I made regarding the optimization of the production line.

3.1 Bottleneck detection

This section answers the question: "How can I detect the bottleneck in the production line?". I will elaborate on the characteristics of a bottleneck in a production line and how I can detect the bottleneck in Plant Simulation.

In Plant Simulation, I can detect the bottleneck by looking at the resource statistics, which show the activities of the workstations (Kikolski, 2016, p. 108). It shows, amongst others, what fraction of the time the workstation is working, waiting and blocked. The bottleneck is the workstation that is working the highest portion of the time (Kikolski, 2016, p. 108). Another characteristic of the bottleneck, in a production line without buffers, is that the workstation after the bottleneck is waiting a high fraction of the time (Kikolski, 2016, p. 108). This can also be seen in the resource statistics.

Another way to detect the bottleneck is to calculate the effective processing speed of each workstation. Consider the following example: workstation 1 has an availability of 5%, having a processing speed of 10 units per minute. Workstation 2 has an availability of 100%, having a processing speed of 1 unit per minute. Thus, the effective processing speed of workstation 1 is 0.5 unit per minute and the effective processing speed of workstation 2 is 1 unit per minute; thus workstation 2 is not the bottleneck, while its utilization is higher than the utilization of workstation 1.

The bottleneck is thus the workstation with the lowest effective processing speed, which can be calculated by multiplying the processing speed of the workstation by the availability of the workstation. The availability of the workstation is the portion of the time that the workstation is operational, which can be calculated as follows: $availability(\%) = 1 - failure\ portion - batch\ changing\ portion$.

3.2 Effects of a standstill of the bottleneck

This section answers the question: "What are the effects when the bottleneck has a standstill?". I will first elaborate on the effects on the workstations in front of the bottleneck and after that, I will elaborate on the effects on the workstations behind the bottleneck.

3.2.1 Effects on workstations in front of the bottleneck

If the bottleneck has a standstill, this means that the workstations in front of the bottleneck are producing products that cannot be processed at the bottleneck. Therefore, these products will accumulate on the production line in front of the bottleneck. This is not directly a problem, however when the production line is fully occupied, the workstations in front of the bottleneck cannot process the products anymore and are said to be 'blocked'. Therefore, the actual throughput, which is part of the Overall Equipment Effectiveness that will be maximized, will decrease in case of a bottleneck standstill.

3.2.2 Effects on workstations behind the bottleneck

If the bottleneck has a standstill, this means that the workstations behind the bottleneck, in case there are no buffers behind the bottleneck, do not have products to process. Therefore, the workstations are waiting for the bottleneck to process the products. The workstations behind the bottleneck can only start processing products again if the bottleneck has recovered from its failure. Therefore, several workstations in the production line are standing still, which decreases the production line throughput.

3.3 Production line optimization methodologies

In the literature, there are methodologies that can be used to improve the performance of the production line by optimizing bottlenecks. One of those methodologies is OPT, also known as Optimized Production Technology, which states that bottlenecks determine the throughput of the production line (Goldratt & Cox, Het doel: Een proces van voortdurende verbetering, 1988, p. 283). Another methodology is the TOC, also known as the Theory of Constraints, which is a methodology that iteratively improves the performance of a production line by exploiting the bottlenecks (Goldratt, Theory of Constraints, 1999). The DBR methodology, also known as the Drum-Buffer-Rope methodology comes from the Theory of Constraints and the Optimized Production Technology. The DBR methodology helps to decide exactly where in a process control should occur because the amount of work loaded onto each workstation in the production line is often not perfectly balanced (Slack, Chambers, & Johnston, 2010, p. 290).

I want to find more information about those three production line optimization methodologies in terms of theory explanation and case studies. Therefore, I will answer the question: "Which production line optimization methodologies exist in the literature and how are they applied in practice?" by means of a systematic literature review. The systematic literature review protocol that I used to find the information in this section is presented in Appendix 2.

In the following sections, I will describe my findings from my systematic literature review. This section is split into three different sub-sections: each section covers one production line optimization methodology regarding theory and case studies. Section 3.3.1 describes the Theory of Constraints, Section 3.3.2 describes the Optimized Production Technology and Section 3.3.3 describes the DBR methodology. Section 3.3.4 gives a summary of my findings with the systematic literature review.

3.3.1 The Theory of Constraints (TOC)

Slack, Chambers, & Johnston (2010) describe the Theory of Constraints. Slack, Chambers, & Johnston (2010) state that any bottleneck will disrupt the smooth flow of items in processes and that is therefore "important to recognize the significance of capacity constraints to the planning and control process" (Slack, Chambers, & Johnston, 2010, p. 449). The Theory of Constraint focusses the attention on the capacity constraints or bottleneck in processes. This methodology consists out of five steps: (1) identify the bottleneck, (2) decide how to exploit the bottleneck, (3) subordinate everything to the bottleneck, (4) eliminate the bottleneck and (5) start again from step 1. The Theory of Constraints is thus an iterative process of eliminating bottlenecks to improve the process during each cycle of this methodology.

Chakravorty & Atwater (2006) conducted a case study on a door manufacturing plant by applying the Theory of Constraints. In this case study, it was found that "the optimal bottleneck resource utilization is less than 100% (specifically 80.3%) and any attempt to increase the utilization brought disastrous results for the door manufacturing plant" (Chakravorty & Atwater, 2006, p. 445). They propose that the advocates of the Theory of Constraints abandon promoting the 100% bottleneck utilization as this activity is wasteful.

Atwater & Chakravorty (2001) critically look at the Theory of Constraints, which states that only the system's primary resource constraint(s) should be scheduled at 100% of capacity and all other resources should have excess capacity. Atwater & Chakravorty (2001) conducted a simulation study that studies how changes in the capacity utilization of a system's two most heavily utilized resources affect the performance of a drum-buffer-rope scheduling system. With this case study, Atwater & Chakravorty (2001) showed that the 100% utilization of the primary constraint is not optimal. This is further explained by using basic queueing theory: "Anyone with a basic understanding of queueing theory knows that if arrival rates always equal or exceed processing speeds, work-in-process (WIP) and lead times will go to infinity" (Atwater & Chakravorty, 2001, p. 260).

3.3.2 The Optimized Production Technology (OPT)

Goldratt & Cox (1988) describe the Optimized Production Technology and present the most important rules of the OPT methodology. Goldratt & Cox (1988) state that the utilization of a non-bottleneck is not determined by its own capacity, but by other constraints in the plant. Also, one hour of standstill of a bottleneck is said to be one hour of standstill for the whole plant. The most important rule of the OPT methodology is that bottleneck determines the throughput of the plant.

Gelders & Van Wassenhove (1985) conducted a case study by looking at production-inventory control systems. Three control systems were used: MRP, JIT and OPT. Gelders & Van Wassenhove (1985) state that there is nothing new in the rules of OPT and that few people will disagree with them. However, Gelders & Van Wassenhove (1985) state that some of these basic rules are not respected in practice. "JIT has a better potential than MRP for respecting them in practice" (Gelders & Van Wassenhove, 1985, pp. 207-208). In terms of capacity utilization, the OPT methodology is very similar to the JIT methodology. Gelders & Van Wassenhove (1985) suggest that the best solution to smooth production when capacity limitations are a problem is to use the "best of three worlds" approach, in which OPT is the first step to plan carefully the bottleneck facilities followed by the use of MRP and JIT.

3.3.3 The Drum-Buffer-Rope methodology (DBR)

Slack, Chambers, & Johnston (2010) describe the drum-buffer-rope methodology. This methodology comes from the Theory of Constraints and the Optimized Production Technology. The DBR methodology describes exactly where in a process control should occur. The work loaded onto each separate work center is often not perfectly balanced, meaning that there is likely to be a bottleneck in the process. Slack, Chambers, & Johnston (2010) state that the bottleneck should be the control point of the whole process, called the drum, as "it sets the 'beat' for the rest of the process to follow" (Slack, Chambers, & Johnston, 2010, p. 290). As the bottleneck does not have sufficient capacity, Slack, Chambers, & Johnston (2010) argue that it is sensible to keep a buffer of inventory in front of the bottleneck to make sure that it has always something to work on. Slack, Chambers, & Johnston (2010) state that "some form of communication between the bottleneck and the input to the process is needed to make sure that activities before the bottleneck do not overproduce" (Slack, Chambers, & Johnston, 2010, p. 290), which is called the rope.

Thürer, Stevenson, Silva, & Qu (2017) conducted a case study on the drum-buffer-rope methodology by comparing this methodology with Workload Control release methods in a pure job shop and a general flow shop with varying levels of bottleneck severity. This case study showed that the workload control method outperforms the DBR methodology in case of low bottleneck severity. However, in terms of high bottleneck severity, the workload control method is outperformed by the DBR methodology, as evenly distributing workloads across resources, which the workload control method attempts to, is functionless in case of a strong bottleneck.

Huang, Pei, Wu, & May (2013) conducted a case study on a mixed production line and the re-scheduling, by applying both the Theory of Constraints and a Drum-Buffer-Rope algorithm. Huang, Pei, Wu, & May (2013) found that the buffer and buffer management are able to manage the production fluctuation. The bottleneck was identified by using the Theory of Constraints and the DBR algorithm was used to determine the buffer size that was needed for the bottleneck. Huang, Pei, Wu, & May (2013) also found that placing a buffer in front of the bottleneck was beneficial to minimize the chances of products to get delayed.

Atwater & Chakravorty (2001) showed that the drum-buffer-rope methodology works very well to relatively low levels of increased capacity at the operation's second most heavily utilized resource.

3.3.4 Summary of Production line optimization methodologies

From this Systematic Literature Review, we have seen that the Theory of Constraints, the Optimized Production Technology and the Drum-Buffer-Rope methodology are very similar. All methodologies are focused on minimizing the negative effects of a bottleneck in a production line. Next to that, all methodologies state that the bottleneck determines the throughput from the production line. These methodologies therefore prescribe to first identify the bottleneck in the production line and after that, to eliminate the bottleneck. The Theory of Constraints and the Optimized Production Technology do not prescribe one type of elimination technique, however the Drum-Buffer-Rope methodology does. The DBR-methodology prescribes that a buffer has to be created in front of the bottleneck to make sure that the bottleneck always has something to work on.

The case studies regarding the Theory of Constraints in this Systematic Literature Review provided very useful information additional to the theory description. Two case studies criticized the Theory of Constraints by mentioning that a 100% utilization of the bottleneck is not optimal. Chakravorty & Atwater (2006) showed that that the optimal bottleneck utilization was 80.3% and that any attempt to increase the utilization brought disastrous results for the door manufacturing plant. Atwater & Chakravorty (2001) explained, by using Queueing Theory, that lead time will go to infinity if the utilization of the bottleneck equals 100%.

The case study on the Optimized Production Technology showed a useful application of the Optimized Production Technology. Gelders & Van Wassenhove (1985) showed that the Optimized Production Technology is very useful to use as a first step to plan the bottleneck facilities, which can be followed by the use of MRP and JIT.

The case studies regarding the Drum-Buffer-Rope methodology in this Systematic Literature Review provided very useful information additional to the theory description. Thürer, Stevenson, Silva & Qu (2017) showed that the DBR-methodology works particularly well in case of high bottleneck severity. Huang, Pei, Wu & May (2013) showed that placing a buffer in front of the bottleneck was beneficial to minimize the chances of products to get delayed, which confirms the theory description. Atwater & Chakravorty (2001) showed that the DBR-methodology works very well to relatively low levels of increased capacity at the operation's second most heavily utilized resource.

3.4 Production line optimization techniques

This section answers the question: "Which production line optimization techniques can I use to optimize the production line?". I will describe three different production line optimization techniques that can be used to optimize the production line. Those different techniques are buffering, the V-curve principle and an extended version of the V-curve principle.

3.4.1 Buffering

One of the production line optimization techniques is buffering. In this section, I will elaborate on buffering in front of the bottleneck and buffering behind the bottleneck and give an estimation of the buffer capacity that is needed.

Buffering in front of the bottleneck

As already described in Section 3.3.3, it is beneficial to buffer in front of the bottleneck, because this will make sure that the bottleneck always has something to work on. The workstations in front of the bottleneck will most of the time work faster than the bottleneck; therefore, line accumulation will occur if there is no buffer space in front of the bottleneck. The buffer space makes it possible to buffer, such that the workstations in front of the bottleneck will not be blocked when the line is fully occupied and can continue to process products.

Next to that, in case a workstation in front of the bottleneck fails, the buffer will make sure that bottleneck can process the items that are currently in the buffer, making sure that the bottleneck has something to work on. The buffer thus makes sure that the bottleneck does not suffer from that workstation failure. Of course, the buffer size determines the extent to which a bottleneck suffers from that workstation failure. The higher the buffer size, the less the bottleneck suffers from that workstation failure.

To optimally benefit from the buffer that is created, the buffer should be able to provide enough products to the bottleneck if the workstation in front of the bottleneck fails. The buffer size thus has to be determined by using data from the workstation in front of the bottleneck. These data are the processing speed and the repair time.

The buffer size between the workstations can be estimated as follows: during a failure, the buffer size should be equal to the number of products that can be processed during that failure. So, if a workstation takes on average 5 minutes to get repaired and the processing speed is 100 products per minute, the buffer between the two workstations should be around 500 products. If the conveyor belt between the workstations can accommodate 100 products, the buffer station should have a capacity of 400 products.

Buffering behind the bottleneck

Next to buffering in front of the bottleneck, it is beneficial to buffer behind the bottleneck. Buffering behind the bottleneck compensates for failures of workstations behind the bottleneck. If a workstation behind the bottleneck fails and there is no buffer space, line accumulation after the bottleneck will occur, which will in time make sure that the bottleneck is 'blocked' and cannot process products. As the bottleneck determines the production line throughput, any time that the bottleneck is 'blocked' leads to a decrease in production line throughput.

A buffer behind the bottleneck makes sure that the bottleneck can still process products in case a workstation behind the bottleneck fails, which means that the bottleneck does not suffer from that workstation failure. Of course, the buffer size determines the extent to which a bottleneck suffers from that workstation failure. The higher the buffer size, the less the bottleneck suffers from that workstation failure.

To optimally benefit from the buffer that is created, the buffer should be able to accommodate the products that are processed by the bottleneck when the workstation behind the bottleneck gets repaired. The buffer size thus has to be determined by using data from the workstation behind the bottleneck and the bottleneck itself. These data are the processing speed and the repair time.

The buffer size between the workstations can be estimated as follows: during a failure, the buffer size should be equal to the number of products that can be processed during that failure. So, if the workstation behind the bottleneck takes on average 3 minutes to get repaired and the processing speed of the bottleneck is 100 products per minute, the buffer between the two workstations should be around 300 products. If the conveyor belt between the workstations can accommodate 100 products, the buffer station should have a capacity of 200 products.

3.4.2 V-curve principle

The V-curve principle is a Line Balancing principle that can be used to optimize a production line. The objective of the V-curve principle is to maximize the output of the bottleneck in the production line (Optimumfx, 2018, p. 4). In this section, I will explain how the V-curve principle can be applied and how the V-curve principle minimizes the negative effects of workstation failures.

V-curve principle: application

The V-curve principle works as follows: the processing speed of the bottleneck in the production line is the base for determining the processing speeds from the other workstations. The processing speeds from the other workstations are determined as follows: the processing speeds from the workstations next to the bottleneck are calculated by multiplying the processing speed from a workstation with a variable 1+a. The processing speed of the workstation that is next to that workstation is calculated by multiplying the processing speed of the bottleneck with $(1+a)^2$, etcetera. However, the processing speeds that are calculated should also be feasible. If the calculated processing speed is higher than the maximum processing speed, the maximum processing speed should be used instead of the calculated processing speed.

An example of the V-curve principle is shown in Figure 3.1, in which the value of 'a' equals 0.10. In this situation, workstation 3 is the bottleneck with a processing speed of 100 items per minute. The graph in this figure has a V-shape; this explains why this technique is called the V-curve principle.

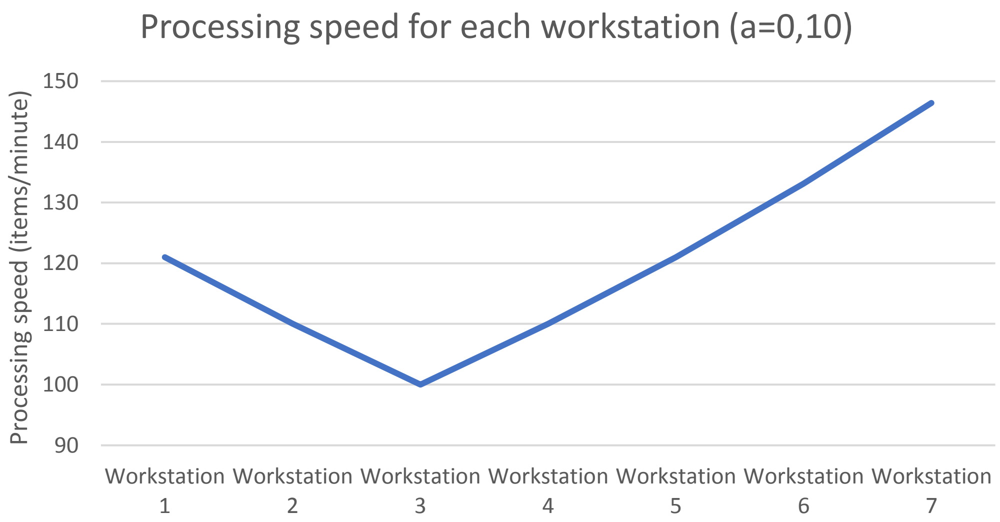


Figure 3.1 | The V-curve principle

V-curve principle: a workstation behind the bottleneck fails

The V-curve principle corrects for workstation breakdowns. In case a workstation behind the bottleneck fails, the production line throughput will not decrease. The production line throughput is determined by the throughput from the bottleneck and the bottleneck can still process products in case another workstation fails. These processed products will accumulate in front of the failed workstation; however, the processing speed of this workstation is higher than the processing speed of the bottleneck, thus this workstation can compensate for its failure. Therefore, the throughput from the production line will equal the throughput from the bottleneck. However, there should be enough space on the production line for products to accumulate. If this is not the case, the V-curve principle will be less effective than is the case when there is a lot of space on the production line for products to accumulate.

V-curve principle: a workstation in front of the bottleneck fails

In case a workstation in front of the bottleneck fails, the production line throughput will not decrease. The production line throughput is determined by the throughput from the bottleneck and the bottleneck can still process products in case another workstation fails. Because of the higher processing speeds from the workstations in front of the bottleneck, a lot of products will be accumulated in front of the bottleneck, such that the bottleneck always has something to work on. However, there should be enough space on the production line for products to accumulate. If this is not the case, the V-curve principle will be less effective than is the case when there is a lot of space on the production line for products to accumulate.

V-curve principle: the bottleneck fails

In case the bottleneck fails, the production line throughput will decrease, as the production line throughput is determined by the throughput from the bottleneck. The V-curve principle cannot minimize the negative effects that are caused by the bottleneck failure. However, because of the higher production speeds from the workstations in front of the bottleneck, the production line will become fully occupied with products in front of the bottleneck, which will make sure that the bottleneck has enough products to process after it has recovered from its failure.

3.4.3 Extended version of the V-curve principle

In this section, I will elaborate on an extended version of the V-curve principle. This extension is that the V-curve only exists after a workstation failure (other than a bottleneck failure) and will continue to exist until the workstation failure is solved (Optimumfx, 2018, p. 4). There are two implementation possibilities for this extended version of the V-curve principle: the V-curve is activated automatically or by the operators. The processing speeds of all workstations first equal the target processing speed of 100 or 60 cans per minute and during a workstation failure (other than a bottleneck failure), the V-curve is activated.

Automatic V-curve activation

To make sure that the extended version of the V-curve principle is as effective as possible, the V-curve should be activated as quickly as possible. This is possible when the V-curve will directly be activated in case of workstation failure (other than a bottleneck failure). To implement this, sensors should be placed on each workstation that can detect a failure. When a failure occurs, this sensor gets triggered and then, the workstation has to "communicate" with other workstations. Those other workstations then have to automatically change their own processing speeds, which will activate the V-curve.

Manual V-curve activation

In case implementing the V-curve automatically is too complicated or too expensive, the V-curve can be activated manually. The effectiveness of the V-curve will, of course, be less than the V-curve when it is automatically activated, because some time, which I estimated at 30 seconds, will be lost due to the manual activation. If a workstation fails (other than a bottleneck failure), then the operator first has to activate the V-curve and then has to solve the workstation failure.

3.5 Choices regarding the optimization of the production line

This section answers the question: “Which production line optimization techniques will be tested in a simulation study?”. I will elaborate on how I will integrate the aforementioned theory in this chapter and how I will experiment with those theories.

3.5.1 Integration of theories

In my experiments with the simulation model of the production line, I will integrate the aforementioned theories in this chapter. At first, I will identify the bottleneck using the resource statistics and the effective processing speed, which is described in Section 3.1. After that, I will perform one iteration of the Theory of Constraints as a production line optimization methodology, as I think that the widely applicable approach of the Theory of Constraints will be perfect to optimize this production line. I will also use additional production line optimization techniques, described in Section 3.4, to support the Theory of Constraints in deciding on how to eliminate the bottleneck.

3.5.2 Experiments with production line optimization techniques

I will perform different experiments with buffering in front of the bottleneck and behind the bottleneck, the V-curve principle and the extended version of the V-curve principle. For all experiments, I will evaluate the values of the KPIs described in Section 2.5 and based on that, I will determine which production line optimization technique has the best overall score on the KPIs. This production line optimization technique will then be used to optimize the production line.

Now that a lot of information is collected about production line optimization techniques, a conceptual model of the production line can be created. The conceptual model of the production line is discussed in Chapter 4, in which simplifications in the simulation model, input data and output data are presented.

4 Conceptual model of the production line
In this chapter, I will create a conceptual model of the production line. I will answer the following research question in this chapter: "What does the conceptual model of the combined production line look like?". This chapter is structured as follows:

- Section 4.1 describes the simplifications that can be made in the simulation model.
- Section 4.2 describes the input variables for the simulation model.
- Section 4.3 describes the output variables of the simulation model.
- Section 4.4 gives a summary of the conceptual model of the production line.

4.1 Simplifications in the simulation model
This section answers the question: "What simplifications can be made in this simulation model?". These simplifications are split into three sections, namely general simplifications, workstation simplifications and simplifications regarding lack of data.

4.1.1 General simplifications
This section describes the general simplifications. These simplifications include the exclusion of the operator from the simulation model, the exclusion of rejected products and the exclusion of the palletizer.

The operator is excluded from the simulation model

In my simulation model, I will not model an operator. One operator will monitor this production line, however in case two workstations fail at the same time, an operator from another line, which will be situated next to this production line, will help the operator from this production line.

One example of this situation is as follows: at a certain moment, the sleever fails and has to be repaired, so the operator repairs the sleever. However, during the repair process, the labeler also fails. As the operator is currently repairing the sleever, the operator cannot repair the labeler at the same moment. However, as there are no failures on the other line at this moment, the operator from the other line helps the other operator by repairing the labeler.

As the probability that three failures occur in a very short time period is less than 5%, which is calculated in Appendix 3, the assumption can be made that no more than two failures occur at the same time. Next to that, the other line is very constant and almost no failures occur. As there is almost always a second operator available to repair a workstation, in case another workstation has also failed, not modeling the operators in the simulation model doesn't have negative effects. In case the probability was big that three failures occur in a very short time period, modeling the operators should have been necessary.

No products are rejected

All the products that are produced are assumed to be of good quality, meaning that they can be delivered to the customer. I will not model that products can get rejected at the end of the production process, as the rejection percentage is very small (less than 0.1%), according to my supervisor at Company X. As the rejection percentage is very small, this assumption will have little impact on the simulation model. Thus, the product quality equals 100%, which is also mentioned in Section 2.5.1.

Palletizer is not modeled in the simulation

I have chosen to not model the palletizer in the simulation. The simplification is made because the palletizer has enough capacity to handle the full pallets. As the palletizer therefore does not influence the production line throughput, I excluded it from the simulation model.

4.1.2 Workstation simplifications
This section describes the workstation simplifications. There are different types of workstation simplifications that I made, which are described below.

Large failures are not considered in the simulation model
Of course, some large failures will occur during the production process. This means that the workstations are not operational for a very long time, for example for 12 hours. As this repair time is so long, there is no possibility to buffer against such a failure or minimize the effects of this failure by using the V-curve principle. Therefore, I have excluded large failures with a very long repair time and I will only focus on small failures. Because large failures are excluded, the average throughput and the OEE in the simulation will be somewhat optimistic, taking into account that these large failures are excluded from the calculation of the average throughput and the OEE.

Track and trace labeler has no processing time and cannot fail
The track and trace labeler has no processing time and cannot fail. This simplification is made because no data is known about the future track and trace labeler. Also, the current track and trace labeler has a low processing speed, which will almost certainly make sure that the track and trace labeler will be the bottleneck when the current track and trace labeler is included in the simulation model. As the track and trace labeler will probably not be the bottleneck in the future production line, I have chosen to give the track and trace labeler no processing time. Next to that, I have excluded failures from this workstation, such that this workstation will not affect the throughput.

Packing machine
As the processing size of the packing machine cannot directly be modeled via an AssemblyStation in Plant Simulation, I have modified the processing time in my simulation model. I have divided the processing time by the workstation processing size, such that a batch can be processed in the same time as when there is a workstation processing size. The failure time remains equal. This simplification will not affect the simulation, as the packing machine has overcapacity in comparison to its successor, the tape machine, and the tape machine has a processing size of 1 box. The packing machine can therefore only send one box to the tape machine, which makes a processing size bigger than one useless for the packing machine, taking into account that the packing machine places the cans in the boxes in parallel.

4.1.3 Simplifications regarding lack of data
This section describes the simplifications regarding lack of data. Two types of lack of data are described below.

Uniformly distributed batch changing time
As there is no data about the individual batch changing times, it is not possible to fit a probability distribution for the batch changing times. However, as the mean batch changing time is expected to be around 10 minutes for the future production line, I will slightly correct for the experience and the skill of the operators by creating a uniform distribution between 8 and 12 minutes for the batch changing time.

Failure distributions
As I do not have data about individual failures and repair times and I only have data about the Mean Time To Failure and the Mean Time To Repair, which I requested from the operators and asked for verification from the production manager, I have assumed statistical distributions that belong to the failure times and the repair times. An explanation on the distributions that I have chosen is shown in Section 4.2.2.

4.2 Input data for the simulation model

This section answers the question: "What are the input data for the simulation model?". In this section, I will elaborate on product data, workstation data, target data, line data, a conceptual process model and the production line layout.

4.2.1 Product data

The following product data are input for the simulation model: product groups, product sizes and the production scheme of the products. These data will be elaborated upon in this section.

Product groups

The product groups that will be used in the simulation are depicted in Table 4.1 below, of which an explanation is shown in Section 2.1.3.

Product group	Type of product	Sleeve?	Label on can?	Packed in a box?	Label on box?
5L_Type1	5L	YES	NO	YES	YES
5L_Type2	5L	NO	YES	YES	YES
10L_Type1	10L	YES	NO	NO	NO
10L_Type2	10L	NO	YES	NO	NO
10L_Type3	10L	YES	YES	NO	NO

Table 4.1 | Product groups

Product sizes

The product sizes are as follows: the 5L can has the size 185 x 135 x 283 mm (length x width x height), the 10L can has the size 234 x 191 x 308 mm, and the boxes for the 5L can (two 5L cans are placed in one box) has the size 274 x 185 x 283 mm. These product sizes are important input variables for the simulation model, as the product sizes determine the line capacities, which are automatically calculated in Plant Simulation, using these product sizes.

Production scheme

There are two production schemes: one production scheme for the production of 5L cans and one production scheme for the production of 10L cans. To reduce batch changing times, a production scheme will consist of only 5L cans or only 10L cans. For simplicity, there are two production schemes that will be used in the simulation model. Those production schemes are presented in Table 4.2 below. These schemes contain 13 batches with a size of 10,000L. Thus, in each batch, either 2000 5L cans are produced or 1000 10L cans.

The batch size of 10,000L is chosen based on a batch size optimization analysis, which was part of another bachelor assignment, according to my supervisor at Company X. If the batch size is low, this will mean that inventories of those products can be controlled a lot better. However, the batch changing time will be relatively large compared to the batch processing time. If the batch size is large, this will mean that the batch changing time is relatively low compared to the batch processing time. However, the inventories of those products can be controlled less efficient, because the inventory will often be too high. The batch size of 10,000L is thus a trade-off between on the one hand the batch changing time compared to the batch processing time and on the other hand the efficiency of the inventories.

Batch number	Production scheme 5L cans	Production scheme 10L cans
1	5L_Type1 (2000)	10L_Type1 (1000)
2	5L_Type2 (2000)	10L_Type2 (1000)
3	5L_Type2 (2000)	10L_Type3 (1000)
4	5L_Type1 (2000)	10L_Type3 (1000)
5	5L_Type1 (2000)	10L_Type1 (1000)
6	5L_Type2 (2000)	10L_Type1 (1000)
7	5L_Type2 (2000)	10L_Type2 (1000)
8	5L_Type1 (2000)	10L_Type3 (1000)
9	5L_Type1 (2000)	10L_Type2 (1000)
10	5L_Type2 (2000)	10L_Type2 (1000)
11	5L_Type2 (2000)	10L_Type1 (1000)
12	5L_Type1 (2000)	10L_Type1 (1000)
13	5L_Type2 (2000)	10L_Type3 (1000)

Table 4.2 | Production schemes

When looking at, for example, the second and third batch of the 5L cans, both batches consist of 5L_Type2. This does not mean that Batches 2 and 3 consist of the same product, however they are from the same product group that I specified in Section 2.1.3 and Section 4.1.1. Examples of what products could be in Batches 2 and 3 are not presented because of confidentiality agreements.

4.2.2 Workstation data

The following workstation data are input for the simulation model: processing speeds per product, workstation processing sizes, workstation cycle times, failure data and the batch changing time. These data will be elaborated upon in this section.

Processing speeds per product

The maximum processing speeds per product are presented in Table 4.3 below. When a product group does not pass a certain workstation, the processing speed is not filled in. All processing speeds are presented in products per minute. The processing speeds are deterministic, according to a lot of operators and my supervisor that I consulted to acquire information about the processing speeds.

	5L_Type1	5L_Type2	10L_Type1	10L_Type2	10L_Type3
Depalletizer	100 cans	100 cans	60 cans	60 cans	60 cans
Sleever	120 cans	-	72 cans	-	72 cans
Filler/capper	100 cans	100 cans	60 cans	60 cans	60 cans
Labeler	-	120 cans	-	72 cans	72 cans
Box erector	60 boxes	60 boxes	-	-	-
Packing machine	65 boxes	65 boxes	-	-	-
Tape machine	60 boxes	60 boxes	-	-	-
Box labeler	60 boxes	60 boxes	-	-	-

Table 4.3 | Processing speeds (products / minute)

Workstation processing size

In Table 4.4, the workstation processing sizes are presented. Next to that, the way in which products are processed is presented. The first option is that the products are processed parallel, meaning that several products are processed at exactly the same moment. An example of this is the packing machine. This workstation waits until five boxes and 10 5L cans have arrived at this workstation. If this is the case, the 10 5L cans are placed in the 5 boxes simultaneously. The second option is that the products are processed in series. This is the case with the future filler/capper in which 43 cans are filled and capped in series, meaning that the filling of the first can begins slightly earlier than the filling of the second can.

	5L	10L	Parallel or series?
Depalletizer	54 cans	30 cans	Parallel
Sleever	20 cans	16 cans	Series
Filler/capper	43 cans	43 cans	Series
Labeler	1 can	1 can	Series
Box erector	4 boxes	0	Series
Packing machine	5 boxes	0	Parallel
Tape machine	1 box	0	Series
Box labeler	1 box	0	Series

Table 4.4 | Workstation processing sizes

Workstation cycle time

The time spend in a workstation by a product, the workstation cycle time, is much longer than the processing time of a product in a workstation. The product often stays in the workstation, while the product behind that product is processed.

Therefore, this workstation cycle time has to be used in the simulation as the processing time of a product in a workstation. The workstation cycle time can be calculated by multiplying the processing time (in units per minute) by the workstation processing size. So, the formula to calculate the workstation cycle time (in seconds) can be described as follows:

$$\text{workstation cycle time} = \text{processing time} \times \text{processing size} = \frac{60}{\text{processing speed}} \times \text{processing size}$$

The workstation cycle time of the filler capper during a 5L batch is, for example:

$$\text{workstation cycle time} = \frac{60}{\text{processing speed}} \times \text{processing size} = \frac{60}{100} \times 43 = 25.8 \text{ seconds}$$

While the processing time is only 0.6 seconds, the workstation cycle time in the workstation is 25.8 seconds.

Failure data

Regarding the Time To Failure, only the Mean Time To Failure (MTTF) is known. However, the failure behavior of some workstations is known, as it depends on the number of products that are processed by that workstation. This is the case with the sleever, the labeler, the tape machine and the box labeler. These failures do not occur at random, but after a certain number of products is processed. After a certain number of products are processed, the sleeves, labels and the tape have to be replaced. This number is not always the same, but fluctuates a little bit, depending on the number of sleeves, labels or tape that are lost during the replacement process or left over from a previous batch.

As the MTTF is known, I assume that the TTF of these workstations is uniformly distributed, with a deviation of 25% of the mean. This deviation is called DeviationPercentageMTTF in the simulation model and this percentage will be varied in the experiments in Chapter 6. So, the left bound of the interval equals 75% of the MTTF and the right bound of the interval equals 125% of the MTTF. The uniform distribution makes sure that the failure always occurs around the MTTF and the interval makes sure that the possible deviation from the MTTF is considered.

The failure behavior is not known for the depalletizer, filler/capper, box erector and the packing machine. As only the MTTF is known, I assume that failures regarding these workstations occur at random. The exponential distribution is suitable for random Time To Failures (Robinson, 2014, p. 139) and is therefore a good distribution to model these failures.

The repair time distribution is also not exactly known. I requested the repair times, including failure detection time and walking time, from the operators and asked for verification from the production manager. As the repair times differ a lot for each type of failure, I assume that the repair time is uniformly distributed, with a deviation of 25% of the mean. This deviation is called DeviationPercentageMTTR in the simulation model and this percentage will be varied in the experiments in Chapter 6. So, the left bound of the interval equals 75% of the MTTR and the right bound of the interval equals 125% of the MTTR.

In Table 4.5, all the failure data are depicted. For each workstation, I have depicted the MTTF and the MTTR and the distribution that is used to model failures and repair times.

	MTTF (minutes)	TTF distribution	MTTR (minutes)	TTR distribution
Depalletizer	30	Exponential	1.5	Uniform
Sleever	30	Uniform	6	Uniform
Filler/capper	1440	Exponential	2	Uniform
Labeler	30	Uniform	3	Uniform
Box erector	1440	Exponential	2	Uniform
Packing machine	1440	Exponential	2	Uniform
Tape machine	60	Uniform	2	Uniform
Box labeler	30	Uniform	3	Uniform

Table 4.5 | Failure data

Right now, I have set the deviation percentage regarding the uniform distribution at 25%. As this deviation percentage cannot be calculated because of a lack of data, I will perform a sensitivity analysis on this deviation percentage, which is described in Chapter 6.

Batch changing time

As mentioned earlier in Section 2.3, the batch changing time differs for each type of product. Next to that, the batch changing time is dependent on the experience and the skill of the operators. As the mean batch changing time is expected to be around 10 minutes for the future production line, I will slightly correct for the experience and the skill of the operators by creating a uniform distribution between 8 and 12 minutes for the batch changing time.

4.2.3 Target data

The target throughput for the 5L cans is a throughput of 100 cans per minute and the target throughput for the 10L cans is a throughput of 60 cans per minute.

4.2.4 Line data

Regarding the conveyor belt between the workstations, there are two important parameters: the distance between products and the line speeds. There is no distance between products on the conveyor belts, thus the cans and boxes are placed against each other on the conveyor belts. The line speed of the conveyor belts is 1 m/s which I have measured with a stopwatch.

4.2.5 Conceptual process model

In this section, the conceptual process model of the production process of a 5L_Type1 product is presented in Figure 4.1. The start of the process is the arrival of a new product, which is the first product of the first batch. After that, that product goes through the production process, depicted by the large square, after which the check whether a batch is finished is performed. If the batch is not finished, the next product goes through the production process. If the batch is finished, there is a batch change. If there are still batches to be produced, the process starts over again. If there a no batches to be produced anymore, the production scheme is completely produced and the process ends.

As there are five different product types, I have created four conceptual process models for each product type, which are depicted in Appendix 4.

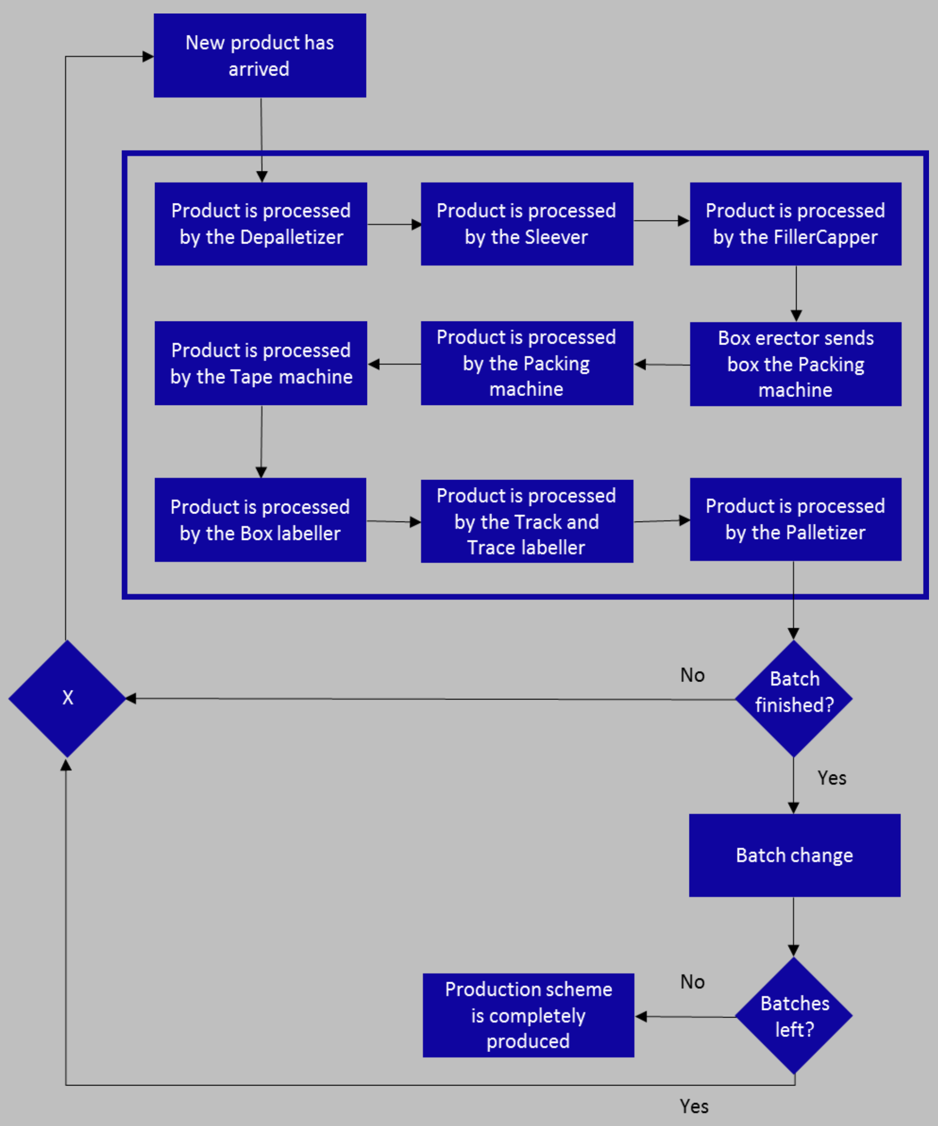
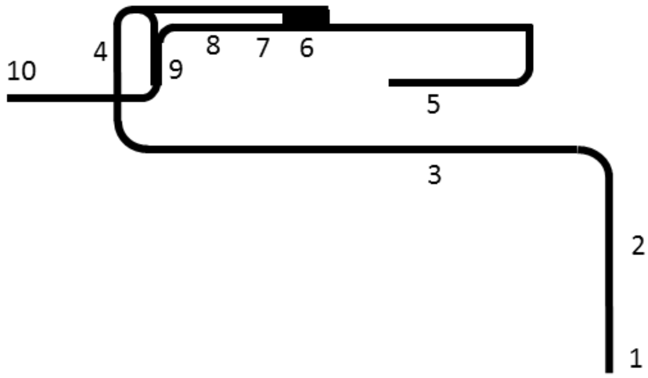


Figure 4.1 | Conceptual process model of a production process of a 5L_Type1 product

4.2.6 Production line layout

In Figure 4.2, the production line layout is presented. Each workstation is depicted in this figure with a number, which is linked to the workstation. Due to confidentiality agreements, the original layout is not depicted. Therefore, a simplified version of the layout is created.



1. Depalletizer
2. Sleever
3. Filler/capper
4. Labeler
5. Box erector
6. Packing machine
7. Tape machine
8. Box labeler
9. Track and trace labeler
10. Palletizer

Figure 4.2 | Production line layout

4.3 Output variables of the simulation model

This section answers the question: "What are the output variables of the simulation model?". The two KPIs mentioned in Sections 2.5.1 and 2.5.2 are presented, including a short explanation.

- **Average throughput:** This variable gives the average throughput per minute in which batch changing times are excluded. This variable will be used to assist in calculating the Overall Equipment Effectiveness.
- **Overall Equipment Effectiveness (OEE):** This variable will be calculated by using the Availability and the Performance, as stated in Section 2.4.

4.4 Summary

In this chapter, a conceptual model for the production line was created. First, a lot of simplifications have been made: general simplifications, workstation simplifications and simplifications regarding lack of data.

After that, the input data for the simulation model was presented in terms of product data, workstation data, target data, line data, the conceptual process model, and the production line layout. The input data was collected by conducting interviews with both the operators and the management team of Company X.

Finally, the output variables for the simulation model were presented. The Average Throughput and the Overall Equipment Effectiveness will be measured in the simulation model. These output variables should be maximized by means of a simulation study, as requested by the management team.

Now that the conceptual model of the production line is finished, the production line can be implemented in a simulation model. After that, the simulation model has to be verified and validated. All of this is described in Chapter 5.

5 Implementation, verification and validation of the simulation model

In this chapter, I will implement, verify and validate the simulation model of the production line. I will answer the following research question in this chapter: “How can I implement, verify and validate the simulation model?”. This chapter is structured as follows:

- Section 5.1 describes the implementation of the simulation model.
- Section 5.2 describes the verification and validation of the simulation model.
- Section 5.3 gives a summary of the implementation, verification and validation of the simulation model.

5.1 Implementation of the simulation model

This section answers the question: “How can I implement the simulation model?” I will present the simulation model that I have created and I will explain how the simulation model works in general.

5.1.1 Presentation of the simulation model

In this section, the simulation model is presented. In Figure 5.1, the part of the model containing the methods, the data and the input and output variables is presented.

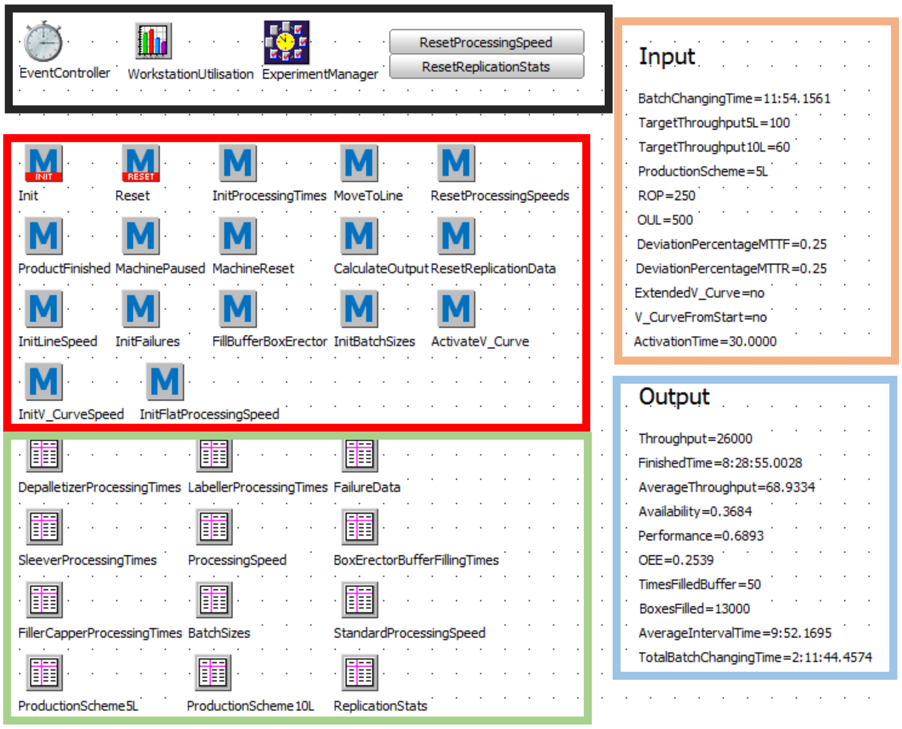


Figure 5.1 | Part 1 of the simulation model

In the red box, the methods are presented in which I have programmed the simulation model. In the green box, the table files containing part of the data described in Chapter 4 are presented. In the orange box, a part of the data described in Chapter 4 is presented. In the blue box, the output data described in Section 4.3 is presented. In the black box, the objects needed to run the simulation model are presented.

In Figure 5.2 the part of the model containing the production line is presented. This part is created on scale, meaning that it is a small representation of the future production line. The sleever and the depalletizer are not depicted in this figure since this part of the simulation model does not fit into one picture.

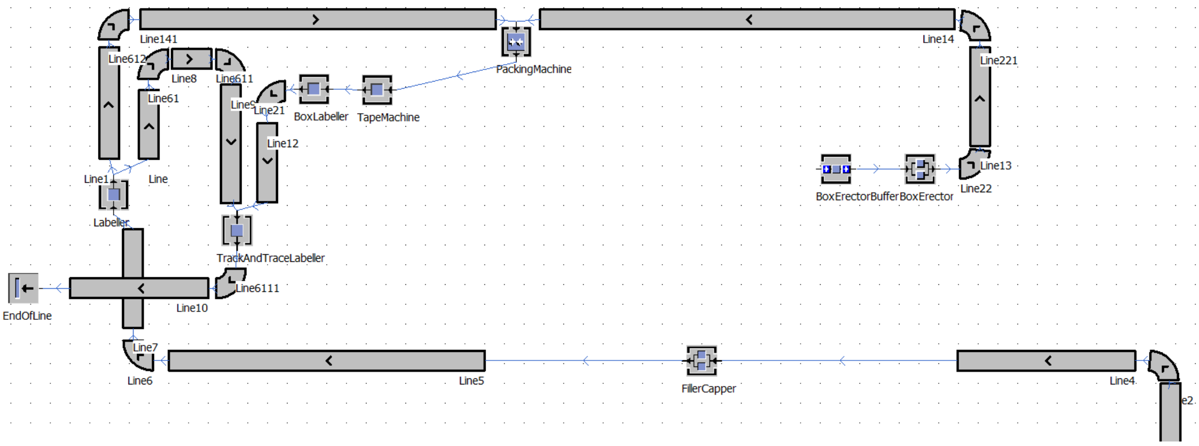


Figure 5.2 | Part 2 of the simulation model

5.1.2 How the simulation model works in general

This section describes how the simulation model works in general. It is split into different chronological subsections, which are the big building blocks of the simulation model.

Initialization

In this phase, the simulation model is initialized. At first, the data that is stored into the table files regarding workstation processing sizes, processing times, line speed, and failures is initialized. All these data are input data for the workstations and the conveyor belt. After having initialized the data, the simulation model checks whether a 5L or a 10L production scheme has to be finished. After determining that, the simulation model creates the first batch of the production scheme that has to be finished and places those products in front of the depalletizer. In case a 5L production scheme has to be finished, the simulation model creates boxes such that the buffer in front of the box erector is fully occupied.

Production phase

In this phase, one batch of products is produced. The products flow through the simulation model and during production, workstation failures can occur which have to be solved. Next to that, the simulation model has a counter at the end of the production line, which measures how many products have been produced; this counter can thus determine when a batch is finished.

Batch changing process

When a batch is finished, all the workstations (except the depalletizer) are paused for, on average, 10 minutes. During the batch changing process, it is possible that a workstation is repaired. Because of that and the fact that the pausing time is needed to calculate the resource statistics of the workstations (described in the next paragraph), the batch changing process is modeled in the simulation. After the batch changing process is finished, the next batch in the production scheme is created and placed in front of the depalletizer. After that, the production phase starts again.

Calculation of the output variables

When the counter measures that the production scheme is finished, the output variables are calculated. The average throughput and the OEE are calculated at this moment, for example. Next to that, a report containing the resource statistics of all the workstations is created, showing the different states of the workstations during the simulation.

5.2 Verification and validation of the simulation model

This section answers the questions: “How can I verify the simulation model?” and “How can I validate the simulation model?”. Verification is the process of ensuring that the model design (conceptual model) has been transformed into a computer model with sufficient accuracy (Davis, 1992). Validation is the process of ensuring that the model is sufficiently accurate for the purpose at hand. (Carson, 1986).

In this section, I will elaborate on methods of verifying and validating the simulation model. I will first explain the methods that I have used to verify and validate my simulation model and after that, I will explain how I have verified and validated my simulation model.

5.2.1 Explanation on verification and white-box validation

Verification and white-box validation are conceptually different; however, they are both performed continuously throughout model coding (Robinson, 2014, p. 259). With verification, the simulation model is compared to the conceptual model and with white-box validation, the content of the simulation model is compared to the real world.

Robinson (2014) describes three methods of verification and white-box validation, namely checking the code, performing visual checks, and inspecting output reports. Checking the code is possible by explaining the code to my supervisor at Company X; he will check whether the logic in my code is correct. Visual checks can be performed by running the model on slow speed and looking at the events that will happen. I will also step through the model, predict what will happen next and run the model again and check what happens. The output reports will also be inspected by looking at the value of the KPIs and the workstation utilisations.

5.2.2 Explanation on black-box validation

In black-box validation, the overall behavior of the simulation model is considered (Robinson, 2014, p. 260). There are two approaches to perform this form of validation: comparing the simulation model with the real world and comparing the simulation model with another model, for example a Queuing model.

It is not possible to validate the simulation model with input data from the current 5L and 10L production line and check whether the output report from the simulation model matches the output data of the current 5L and 10L production line. The current production lines namely differ a lot from the future production line in terms of layout and the simulation model will therefore not give an accurate representation of the current production lines.

Comparing the simulation model with the real world is also not possible, because the production line is not built yet, however Robinson (2014) proposes the following solution for that: the comparison can be made against the expectations and intuition of those who have a detailed knowledge of the real system, in this case, my supervisor.

Robinson (2014) states that it is very important to perform both black-box validation and white-box validation to guarantee the validity of the simulation model. Different models can namely give the same output, while the inputs are completely different. White-box validation ensures that these types of errors are detected.

5.2.3 Verification and white-box validation of the simulation model

Regarding verification and white-box validation, my supervisor at Company X and I have checked the code for both the 5L production process and the 10L production process, performed visual checks and inspected output reports. We first checked all the code in chronological order, meaning that we checked the code in the chronological sequence that the code is called. We thus first checked the code used in the initialization phase and ended with the code that is used to calculate the output variables, thus following the sequence described in Section 5.1.2. After that, we performed visual checks, when we looked at the product flow through the production line. We especially paid much attention to the batch changing process, in which we looked if the products are only processed at the depalletizer and blocked in front of the sleever. Finally, we inspected the output reports by checking if the output was feasible according to the input parameters.

5.2.4 Black-box validation of the simulation model

Regarding black-box validation of the simulation model, my supervisor at Company X has predicted the average throughput of the production line, when looking at the input variables. He predicted that the average throughput when finishing the 5L production scheme should be between 60 and 70 cans per minute; in the simulation model, this value was 69.5. Next to that, he predicted that the average throughput when finishing the 10L production scheme should be around 45 cans per minute; in the simulation model, this value was 44.3.

I also created a deterministic model of the production line, described in Chapter 7, and with that model, I calculated the average throughput when finishing the 5L production scheme and the 10L production scheme. According to this deterministic model, the average throughput of the 5L production scheme 66.6 cans/minute, which is a difference of 4.69% with the simulation model, and the average throughput of the 10L production scheme was 41.9 cans/minute, which is a difference of 6.97% with the simulation model.

5.3 Summary

In this chapter, the production line was implemented in Plant Simulation. The complete production line was built on scale in the simulation model and this layout was separated from the coding of the simulation model, which consisted of tables, methods, input variables and output variables. The production process was simulated in four stages: the initialization phase, the production phase, the batch changing process, and the calculation of the output variables.

Regarding the verification and the white-box validation of the simulation model, my supervisor at Company X and I did not find any modeling errors. Regarding the black-box validation of the simulation model, the predictions of my supervisor at Company X and the calculations from the deterministic model of the production line were really close to the real value of the average throughput according to my simulation model. Combining both points, I consider my simulation model to be correct, as the simulation model is verified and validated.

Now that the simulation model is implemented, verified and validated, experiments with the production line can be conducted. Before the experiments can be conducted, the experiments have to be prepared and scenarios for the sensitivity analyses have to be created. All of this is described in Chapter 6.

6 Experiments with the simulation model

In this chapter, I will conduct experiments with the simulation model. I will answer the following research question in this chapter: “Which experiments will be conducted in my simulation study?”. This chapter is structured as follows:

- Section 6.1 describes the preparations for the experiments.
- Section 6.2 gives an introduction on the experiments with sensitivity analyses.
- Section 6.3 describes the experiments with the production line optimization techniques.
- Section 6.4 describes additional experiments with the production line.
- Section 6.5 describes the influence of variability on the simulation output.

6.1 Preparations for the experiments

This section answers the question: “Which preparations have to be made before experimenting?” I will elaborate on the nature of the simulation model and simulation output, issues in obtaining accurate simulation results, and dealing with initialization bias.

6.1.1 The nature of the simulation model and simulation output

“The nature of a simulation model and its output affects the means by which accurate results are obtained from a model.” (Robinson, 2014, p. 168). In this section, I will elaborate on the nature of the simulation model and the simulation output.

The nature of the simulation model

There are two types of classifications for a simulation model (Robinson, 2014, p. 168). The first one is a terminating simulation, in which there is a natural endpoint. The second one is a non-terminating simulation, which does not have a natural endpoint. My simulation model has a natural endpoint, namely the point in time at which the complete production scheme is finished.

The nature of the simulation output

There are three different types of simulation output (Robinson, 2014, pp. 168-171). The first one is transient output, which means that the output is constantly changing (Robinson, 2014, p. 168). The second one is steady-state output, which means that the output is varying according to some fixed distribution (steady-state distribution) (Robinson, 2014, p. 169). The third one is steady-state cycle output, which means that the output will cycle through the same series of steady-states (Robinson, 2014, p. 171). My simulation model has transient output, as the average throughput and the OEE goes from 0 to its maximum during each batch and goes to 0 during the batch changing process. Transient output is also in most cases the type of output that results from a terminating simulation (Robinson, 2014, p. 168).

6.1.2 Issues in obtaining accurate simulation results

In this section, I will elaborate on initialization bias and obtaining sufficient output data. “Both issues, if not properly addressed, can lead to results that are biased and so misleading”. (Robinson, 2014, p. 172).

Initialization bias

The removal of initialization bias applies to non-terminating simulations and to terminating simulations in which starting from and returning to an empty condition is not realistic (Robinson, 2014, p. 173). As I have a terminating simulation and the simulation starts from an empty condition and returns to an empty condition, I do not have to deal with initialization bias.

Obtaining sufficient output data

There are two ways to obtain a sufficient amount of output data. The first one is performing a single long run with the model, which is only applicable to non-terminating simulations. The second approach is to perform multiple replications, which is often the only option for terminating simulations (Robinson, 2014, p. 173).

As my simulation model is terminating, I will perform multiple replications, according to the confidence interval method (Robinson, 2014, p. 184). With this method, the number of replications is calculated such that the percentage deviation of the confidence interval about the mean is less than a specified value *d*.

The number of replications can be determined by the following formula, by performing replications until the width of the confidence interval, relative to the average, is smaller than *d* (Robinson, 2014, pp. 184-185):

$$\frac{t_{n-1,1-\propto/2} \times \frac{S}{\sqrt{n}}}{|\bar{X}|} < d$$

where:

n = number of replications
$\bar{X}$ = mean of the output data from the replications
S = standard deviation of the output data from the replications
$t_{n-1,1-\alpha/2}$ = value from Students t-distribution with n-1 degree of freedom and a confidence level of 1 - α/2
d = the percentage deviation of the confidence interval about the mean

"Theoretically, the number of replications required should be analyzed for every experiment performed. In practice, the number is determined from an analysis of the base model alone and then applied to all experiments. As a result, it is worth overestimating the number of replications a little to give a margin of safety." (Robinson, 2014, p. 187). I will also determine the number of replications once according to the base model and then use a safety margin of 50%, such that I do not have to calculate the number of replications for each experiment. The safety margin of 50% is also very high, making sure that the number of replications performed for other experiments will most likely be enough, such that the width of the confidence interval, relative to the average, is smaller than *d*.

6.2 Introduction on experiments with sensitivity analyses

This section answers the questions: "Which experiments, including sensitivity analyses, will be conducted with a simulation study?". I will first elaborate on the type of experiments that will be conducted and I will describe how I will conduct sensitivity analyses on those experiments.

6.2.1 Experiments with the production line optimization techniques

I will perform experiments with the production line optimization methodologies and techniques, described in Chapter 3. Next to that, I will perform experiments in which I do not use production line optimization techniques, to test whether production line optimization methodologies and techniques have an impact on the production line.

I will perform experiments with 5 optimization techniques: (1) Current situation without optimization (2) Current situation with a buffer in front of the bottleneck and behind the bottleneck (3) The V-curve principle (4) The extended V-curve principle with operator activation (5) The extended V-curve principle with automatic activation.

I will perform experiments for both the 5L production scheme and the 10L production scheme. Next to that, I will measure two KPIs: the OEE and the average throughput.

I will also conduct sensitivity analyses on my experiments. I will vary the value of DeviationPercentageMTTF and DeviationPercentageMTTR, which I used to estimate the spread of the failure times and repair times, as described in Section 4.2.2. I have created four situations for my sensitivity analysis, which are depicted in Table 6.1.

Situation	**DeviationPercentageMTTF**	**DeviationPercentageMTTR**
Situation 1	25%	25%
Situation 2	25%	50%
Situation 3	50%	25%
Situation 4	50%	50%

Table 6.1 | Four different situations for the sensitivity analyses

Four big experiments are conducted regarding the OEE of the 5L production scheme, the OEE of the 10L production scheme, the average throughput of the 5L production scheme, and the average throughput of the 10L production scheme. Each of these experiments is described in Section 6.3.

6.2.2 Additional experiments with the production line

In Section 6.4, additional experiments will be performed with the production line. On request of the operators, I will conduct experiments regarding the placement of boxes on the buffer of the box erector. The operators asked if I could calculate the average time between the moments that the buffer is filled.

Next to that, I will perform experiments with the processing speed of the depalletizer, by determining a processing speed that is needed to increase the throughput of the production line. I will also perform experiments with the optimization technique regarding buffering in front of the bottleneck and behind the bottleneck, in determining a suitable buffer size.

6.3 Experiments with the production line optimization techniques

In this section, I will elaborate on the impact of production line optimization techniques. I will test each production optimization technique in different situations, which are depicted in Table 6.1. Of course, the number of replications is important when conducting the experiments with the production line optimization techniques. I have calculated the number of replications that is needed to get a sufficient amount of data for the four big experiments described in Section 6.2.1.

When using the significance level α = 5% and d = 0.05, the maximum number of replications that is needed equals 9. As described in Section 6.1.2, I will use a safety margin of 50%, which makes the number of replications that is needed (when rounding) 15. Thus, I will perform 15 replications of each experiment. The value of ‘d’ for Situation 4 with the most variability is below 0.03, thus 15 replications are enough for each situation described in Table 6.1.

6.3.1 Bottleneck detection

As described in Section 3.5.1, the detection of the bottleneck is the first starting point to optimize the production line. In this section, I will detect the bottleneck by using the two bottleneck detection methods described in Section 3.1. After that, I will compare the outcomes of the two bottleneck detection methods and conclude on which workstation is the bottleneck.

Bottleneck detection method 1: highest working portion

Using the first bottleneck detection method described in Section 3.1, I have identified the potential bottleneck for the 5L production scheme and the 10L production scheme. In the 5L production scheme, the potential bottleneck is the depalletizer, as the depalletizer is working the highest portion of the time, which can be seen in Figure 6.1. In the 10L production scheme, the potential bottleneck is the filler capper, as the depalletizer is working the highest portion of the time, which as can be seen in Figure 6.2.

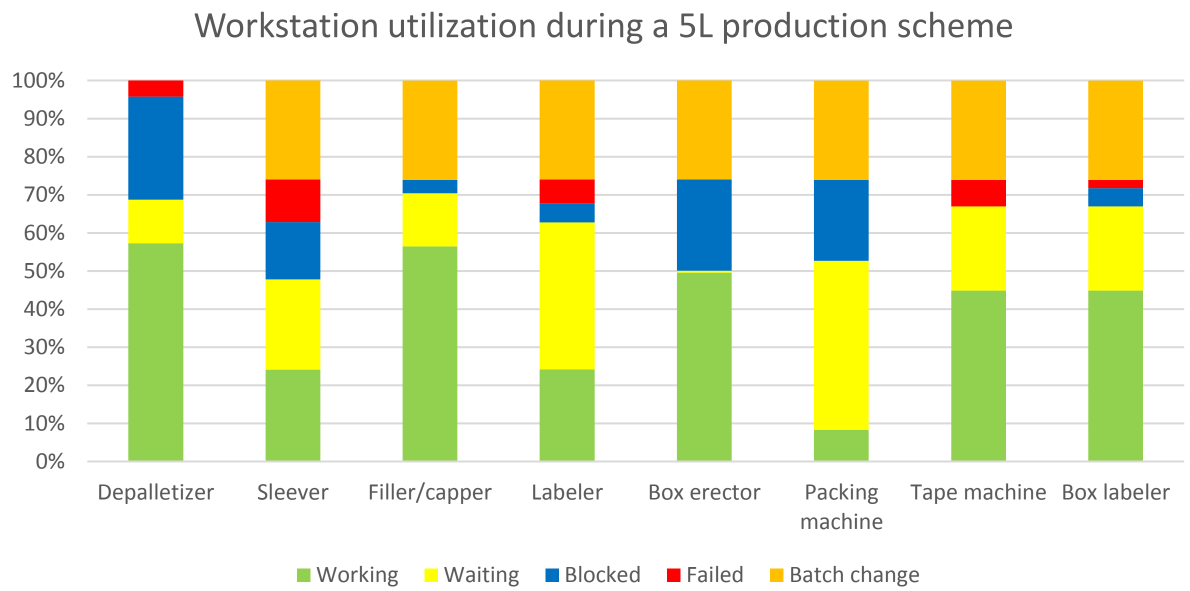


Figure 6.1 | Bottleneck detection for the 5L production scheme

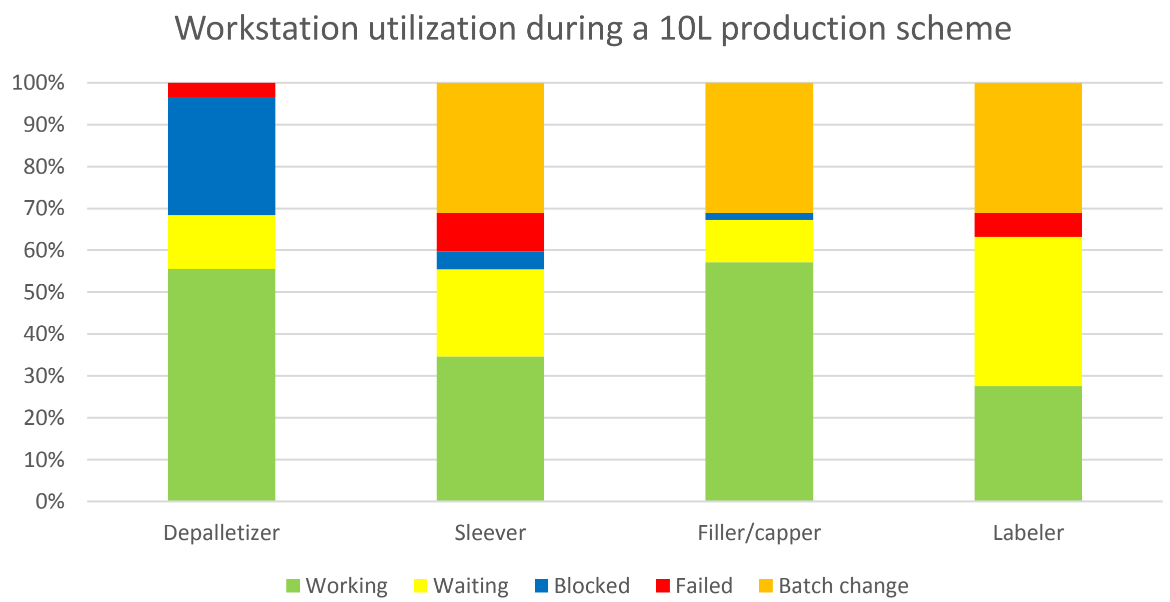


Figure 6.2 | Bottleneck detection for the 10L production scheme

Bottleneck detection method 2: lowest effective processing speed

Using the first bottleneck detection method described in Section 3.1, I have identified the potential bottleneck for the 5L production scheme and the 10L production scheme. In the 5L production scheme, the potential bottleneck is the filler capper, as its effective processing speed is the lowest of all the workstations, which can be seen in Figure 6.3. In the 10L production scheme, the bottleneck is the filler capper, as its effective processing speed is the lowest of all the workstations, which can be seen in Figure 6.4.

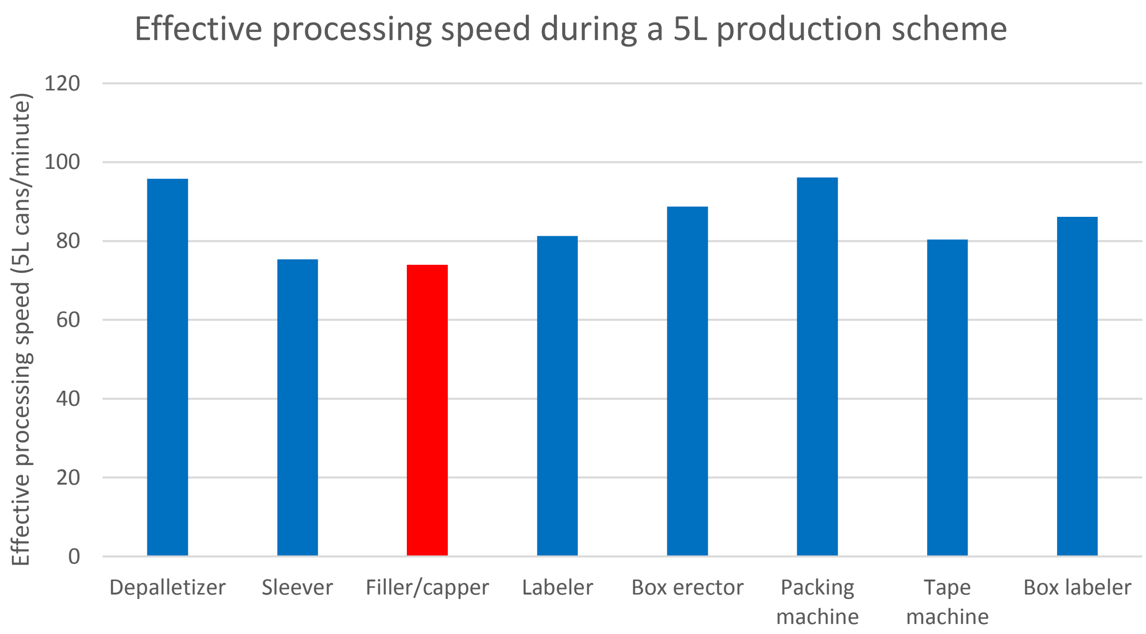


Figure 6.3 | Effective processing speed during a 5L production scheme (5L cans/minute)

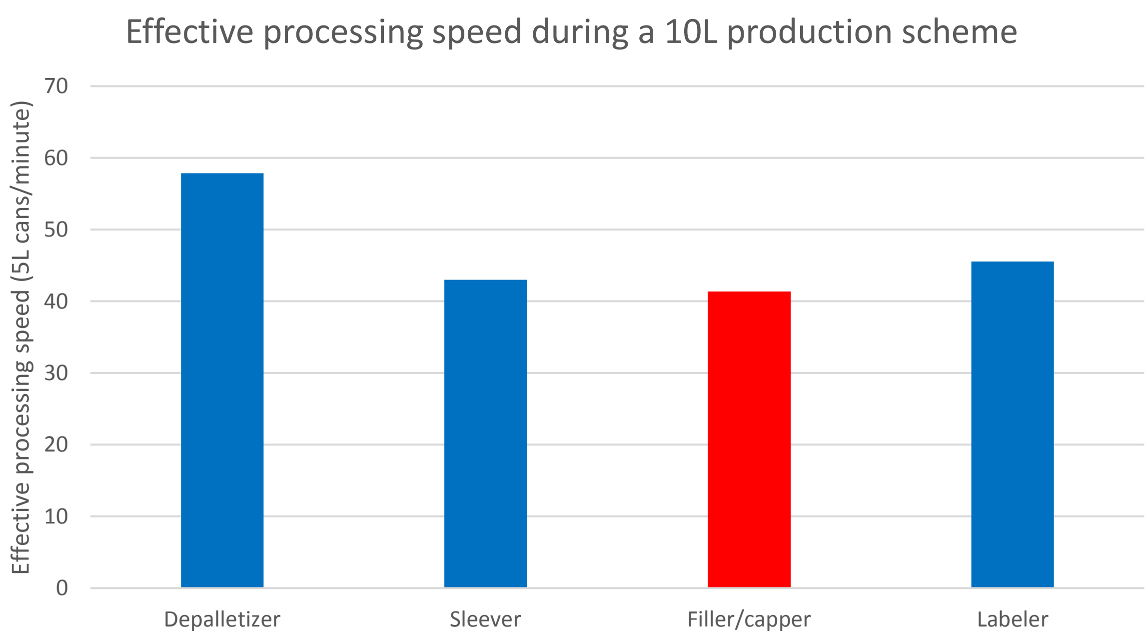


Figure 6.4 | Effective processing speed during a 10L production scheme (10L cans/minute)

Combining the two bottleneck detection methods

The two bottleneck detection methods show different results. The first bottleneck detection method shows that the depalletizer is the bottleneck and the second bottleneck detection method shows that the filler capper is the bottleneck.

I do not think that the depalletizer is the bottleneck, as the depalletizer is blocked for a very high portion of the time, something which is not characteristic for a bottleneck. The filler capper has the second highest working portion (which differs less than 1% from the depalletizer) and is blocked only a tiny fraction of the time.

I will thus treat the filler capper as the bottleneck. To further substantiate this decision, I will perform an experiment with the processing speed of the depalletizer. If increasing the processing speeds does not increase the average throughput by a lot, the depalletizer is not the bottleneck.

6.3.2 Buffering

After having detected the bottleneck, I have created a buffer in front of the filler capper and behind the filler capper, as described in Section 3.4.1. Both buffers have a capacity of 200 cans. This value is unreasonably high but chosen with intent. As there is limited space available, only buffering in height is possible. The height that is needed to accommodate 200 5L cans is 56.6 meters and the height that is needed to accommodate 200 10L cans is 61.6 meters.

When buffering in front of the bottleneck and behind the bottleneck turns out to increase the OEE and/ or the average throughput, additional experiments will be performed in Section 6.4 to find the optimal capacity level of both buffers.

6.3.3 V-curve

As described in Section 3.4.2, the processing speed from the bottleneck is the base for calculating the processing speeds from the other workstations. This processing speed is 100 5L cans per minute or 60 10L cans per minute. Using a value of a = 10%, the processing speeds in the V-curve can be calculated.

I use a value for 'a' of 10% because this value is used in all the examples that I found on the V-curve principle (Optimumfx, 2018; Stewart, 2016; LineView Solutions, 2016).

Regarding the 10L production scheme, the sleever and labeler are next to the filler capper, thus having a processing speed of $60 \times (1 + a) = 60 \times 1.10 = 66$ cans per minute. The depalletizer should then have a processing speed of 72.6 cans per minute, however this exceeds its maximum processing speed.

Regarding the 5L production scheme, the sleever and labeler are next to the filler capper, thus having a processing speed of $100 \times (1 + a) = 100 \times 1.10 = 110$ cans per minute. The depalletizer should then have a processing speed of 121 cans per minute, however this exceeds its maximum processing speed. The packing machine should then have a processing speed of 133 cans per minute, which equals 67 boxes per minute. This, however, exceeds it maximum processing speed. For the tape machine, the box labeler and the box erector, the maximum processing speed will also be exceeded, so their maximum processing speed will be used.

The V-curve principle cannot be applied perfectly because of the fact that the maximum processing speed limits the desired V-curve processing speed. Therefore, there the V-curve will not perform as good as it would perform if the desired V-curve processing speeds could be used instead of the maximum processing speeds.

The processing speeds according to the V-curve, using a = 10% are depicted in Table 6.2 below. If the V-curve processing speed is lower than the maximum processing speed, the maximum processing speed is placed in parentheses after the V-curve processing speed. The sleever, for example, has a V-curve processing speed of 110 5L cans per minute, while its maximum processing speed is 120 5L cans per minute. From this table, it can be seen that the desired V-curve speed often equals the maximum processing speed.

	5L_Type1	5L_Type2	10L_Type1	10L_Type2	10L_Type3
Depalletizer	100 cans	100 cans	60 cans	60 cans	60 cans
Sleever	110 (120) cans	-	66 (72) cans	-	66 (72) cans
Filler/capper	100 cans	100 cans	60 cans	60 cans	60 cans
Labeler	-	110 (120) cans	-	66 (72) cans	66 (72) cans
Box erector	60 boxes	60 boxes	-	-	-
Packing machine	65 boxes	65 boxes	-	-	-
Tape machine	60 boxes	60 boxes	-	-	-
Box labeler	60 boxes	60 boxes	-	-	-

Table 6.2 | Processing speeds using the V-curve principle (products/minute)

6.3.4 Experiments regarding the 5L production scheme

In this section, the results from the experiments with production line optimization techniques regarding the 5L production scheme are presented. I have collected a lot of data with these experiments and I have created 95% confidence intervals regarding the OEE and the average throughput for all of the four situations described in Section 6.2.1. As these figures contain a lot of data, they are a little unclear; therefore, I placed these figures in Appendix 5. The conclusions from the figures are presented in this section.

From Figure A5.1, it can be seen that the OEE does not differ that much for most of the production line optimization techniques. However, the OEE seems to be higher when using the optimization technique regarding buffering in front of the bottleneck and behind the bottleneck.

This is confirmed by creating 95% confidence intervals of the difference in the OEE of the current production line without optimization technique and the production line optimization technique regarding buffering in front of the bottleneck and behind the bottleneck in Figure 6.5. This figure shows, with a confidence level of 95%, that this optimization technique increases the OEE.

In Figure A5.2, the V-curve principle seems to perform the same as the production line without optimization techniques. The extended V-curve principle seems to perform worse than the other optimization techniques. However, the optimization technique regarding buffering in front of the bottleneck and behind the bottleneck seems to outperform the first optimization technique.

This is confirmed by creating a 95% confidence interval of the difference in the average throughput of the current production line without optimization technique and the production line optimization technique regarding buffering in front of the bottleneck and behind the bottleneck in Figure 6.6. This figure shows, with a confidence level of 95%, that this optimization technique increases the average throughput.

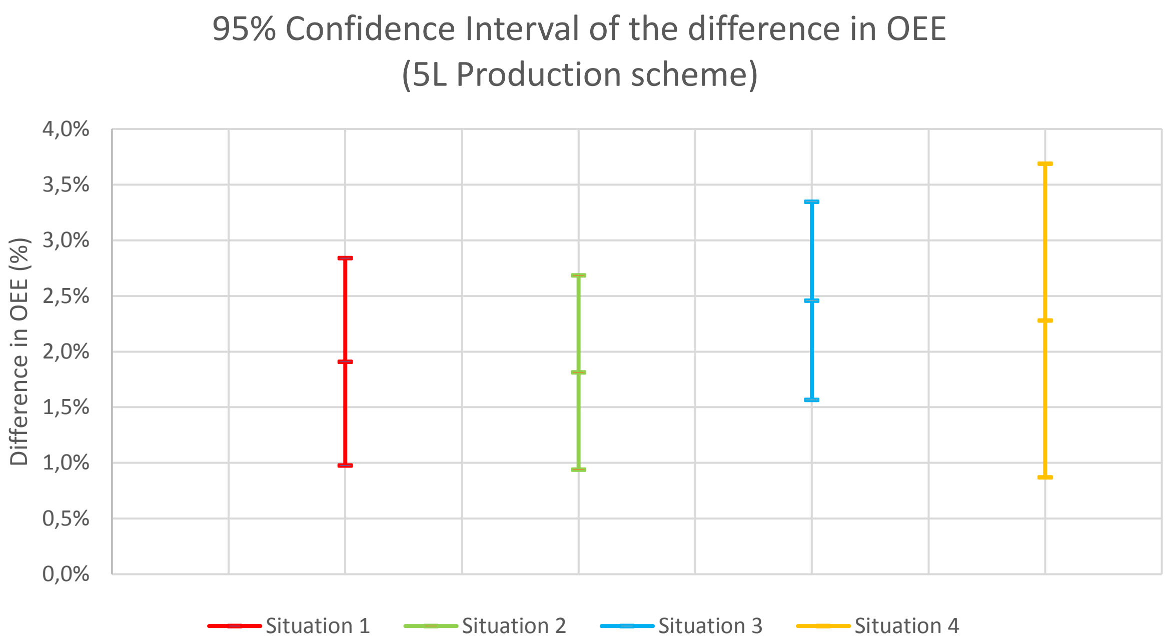


Figure 6.5 | 95% Confidence Interval of the difference in OEE of the 5L production scheme (%)

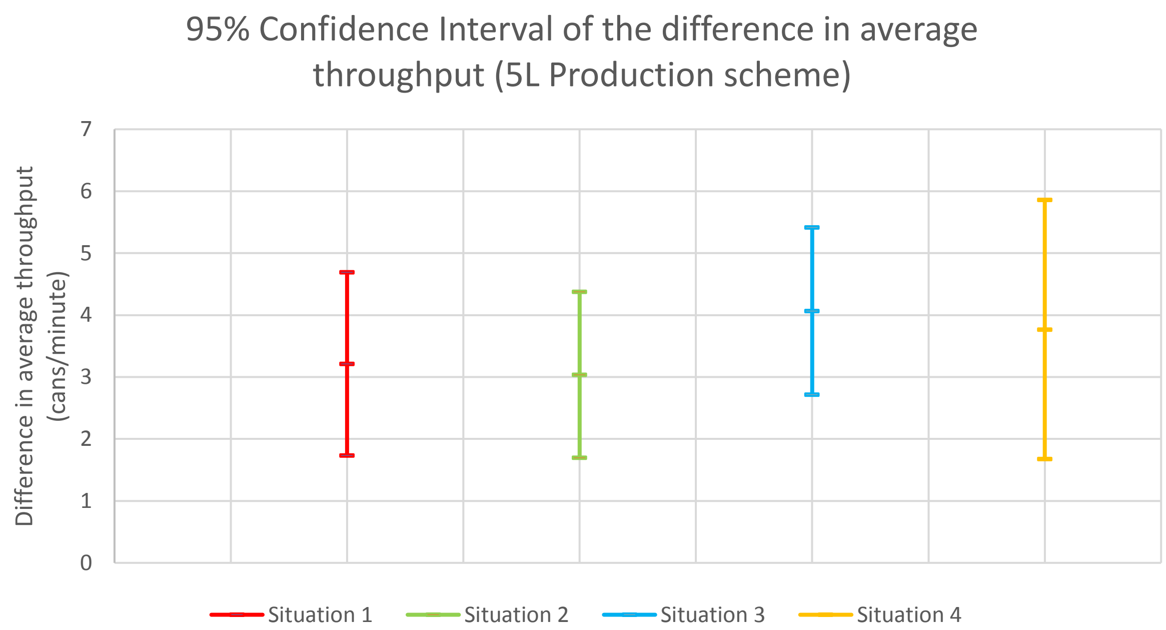


Figure 6.6 | 95% Confidence Interval of the difference in average throughput of the 5L production scheme (cans/minute)

6.3.5 Experiments regarding the 10L production scheme

In this section, the results from the experiments with production line optimization techniques regarding the 10L production scheme are presented. I have collected a lot of data with these experiments and I have created 95% confidence intervals regarding the OEE and the average throughput for all of the four situations described in Section 6.2.1. As these figures contain a lot of data, they are a little unclear; therefore, I placed these figures in Appendix 5. The conclusions from the figures are presented in this section.

From Figure A5.3, it can be seen that the OEE does not differ that much for each of the production line optimization techniques. The OEEs are in the same region and there is no optimization technique that seems to outperform other optimization techniques in terms of the OEE.

From Figure A5.4, it can be seen that the V-curve principle performs equally to the first optimization technique. Next to that, the extended versions of the V-curve principle seem to perform worse than the other three optimization techniques. The optimization technique regarding buffering in front of the bottleneck and behind the bottleneck seems to outperform the first optimization technique.

However, the opposite has been proven in Figure 6.7, in which a 95% confidence interval of the difference in the average throughput of the current production line without optimization technique and the production line optimization technique regarding buffering in front of the bottleneck and behind the bottleneck has been created. This figure shows, with a confidence level of 95%, that this optimization technique does not increase the average throughput.

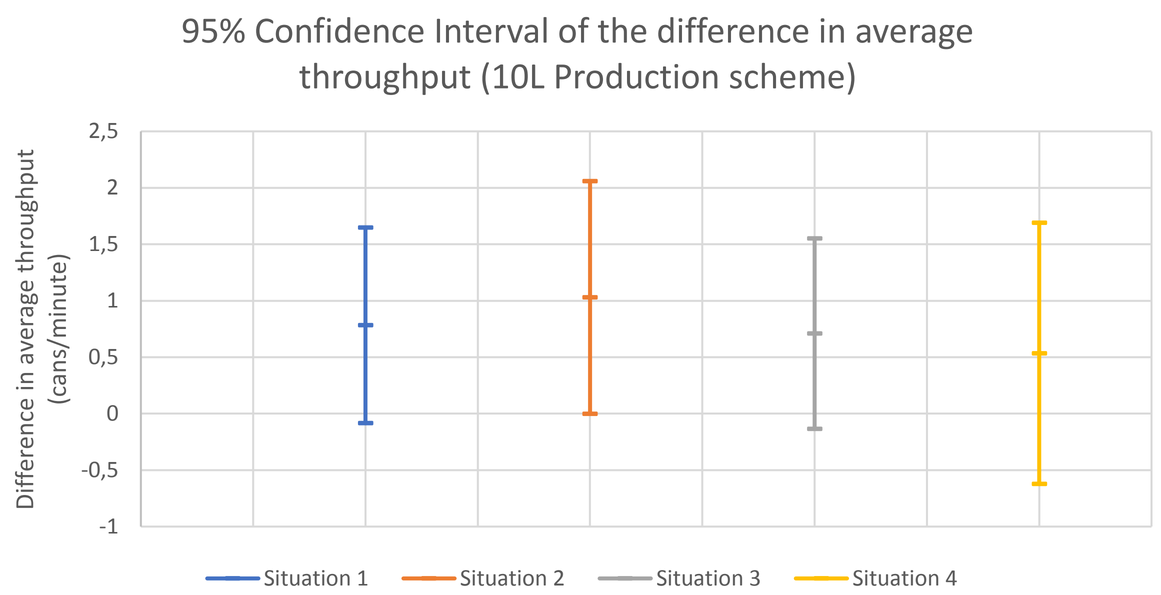


Figure 6.7 | 95% Confidence Interval of the difference in average throughput of the 10L production scheme (cans/minute)

6.4 Additional experiments with the production line

In this section, I will perform additional experiments with the production line. I will first calculate the average time between the moments that the operator has to fill the buffer of the box erector. After that, I will perform experiments with the depalletizer, by determining a processing speed that is needed to increase the throughput of the production line. I will also perform experiments with an optimization technique regarding buffering in determining a suitable buffer size.

6.4.1 Average time between the filling of the buffer of the box erector

In request of the operators, I will determine the minimum buffer capacity that is needed for the buffer of the box erector, taking into account that the average time between the filling of the buffer is feasible for the operators. The buffer for the box erector consists a table, attached to the box erector, with folded boxes on it.

The buffer space is, according to the workstation that is expected to be purchased, 4 meters. These 4 meters of buffer space can accommodate 500 folded boxes. I will perform experiments with a buffer space of 2, 3, 4, 5 and 6 meters to determine the average time between the filling of the buffer. Two meters of buffer space can thus accommodate 250 folded boxes, 3 meters can accommodate 375 folded boxes, etc.

I modeled this filling process in my simulation model with the following logic, which I requested from the operators: at the beginning of a batch, the buffer space is completely filled. When the buffer space is half empty, the operator will fill the buffer space to its maximum capacity. This point at which the operator will fill the buffer space to its maximum capacity is called the re-filling point. The following formula for the re-filling point is thus used in this situation: re-filling point = maximum capacity / 2.

All these points in time in which the buffer is filled are put into a table and at the end of the simulation, the average time between the filling of the buffer is calculated. A current estimation from the operators of the average time between the filling of the buffer is 5 minutes. The operators stated that this time interval is perfectly feasible.

The results of the experiments, which are conducted under 'normal' circumstances, meaning that the experiments are conducted in Situation 1, using no production line optimization technique, are depicted in Table 6.3. The re-filling point is abbreviated to RFP in this table.

Buffer space (m)	RFP (boxes)	Average time between the filling of the buffer (minutes)
2	250	04:48
3	375	07:12
4	500	09:39
5	625	12:04
6	750	14:33

Table 6.3 | Average time between the filling of the buffer

6.4.2 Processing speed of the depalletizer

As the depalletizer seems to be the bottleneck using the first bottleneck detection method in Section 6.3.1, I have performed experiments with the processing speed of the depalletizer, under 'normal circumstances', meaning that the experiments are conducted in Situation 1, using no production line optimization technique.

As the current processing speed is 100 5L cans per minute or 60 10L cans per minute, I will perform experiments with speed increases of 10 5L cans per minute and 5 10L cans per minute. I will create confidence intervals of the average throughput for each experiment, which are depicted in Figure 6.8 and Figure 6.9, respectively.

Figure 6.8 shows interesting results, as it can be concluded, using a significance level of 95%, that increasing the processing speed of the depalletizer does not increase the average throughput of the production line when finishing a 5L production scheme, except in case of a processing speed of 120 cans per minute. This processing speed will increase the average throughput with a significance level of 95%, however the average increase will only consist of an additional 1.5 can per minute, resulting in an increase of 2.27%.

As it is quite strange that the average throughput is higher when the depalletizer has a processing speed of 120 5L cans per minute than with a processing speed of 150 10L cans per minute, I think that the measurement with the processing speed was an outlier, having very favorable random number streams.

Figure 6.9 shows comparable results, as it can be concluded, using a significance level of 95%, that increasing the processing speed of the depalletizer does not increase the average throughput of the production line when finishing a 10L production scheme.

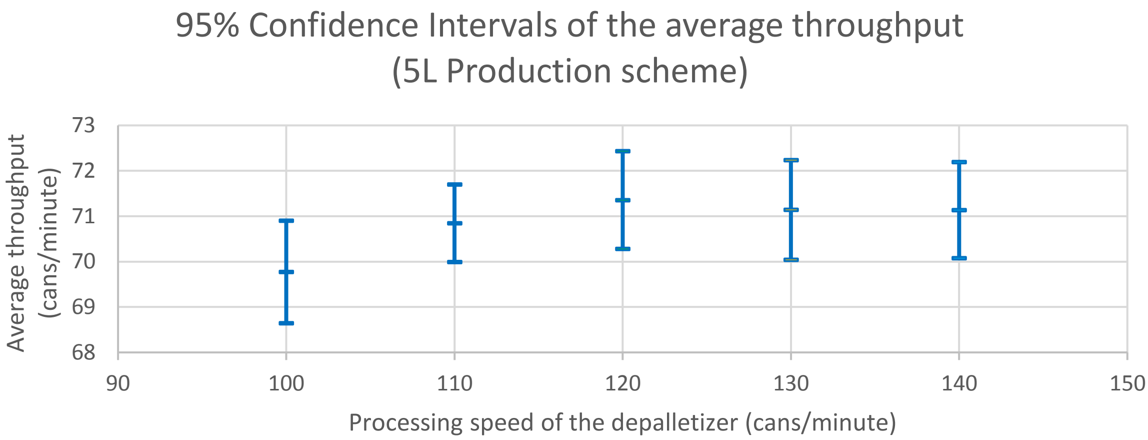


Figure 6.8 | 95% Confidence intervals regarding the average throughput of the 5L production scheme (cans/minute)

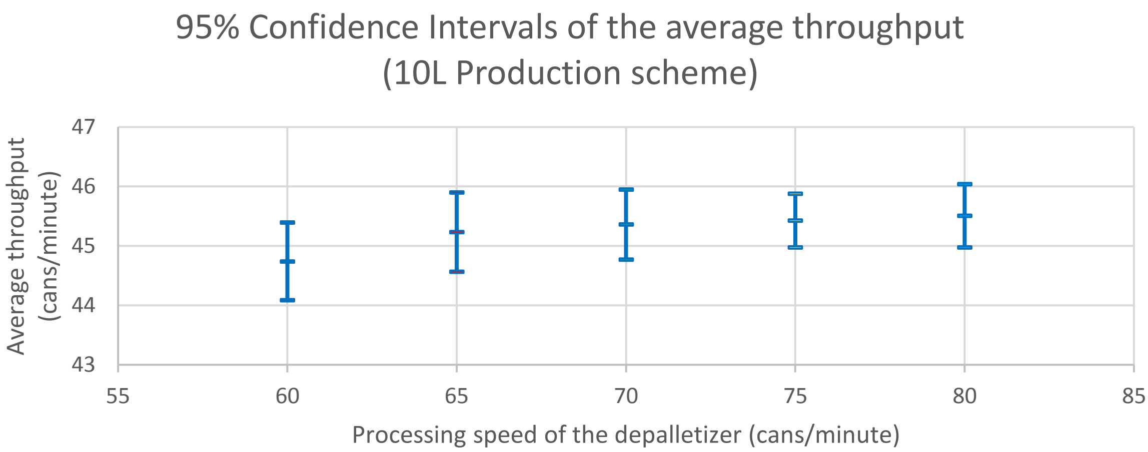


Figure 6.9 | 95% Confidence intervals regarding the average throughput of the 5L production scheme (cans/minute)

6.4.3 Determining a suitable buffer size for the buffers next to the bottleneck

In this section, I will conduct experiments to find a suitable buffer size for the buffers next to the bottleneck, which are used in the second optimization technique. This optimization technique increases the average throughput of the production line when finishing a 5L production scheme, as shown in Section 6.3.4.

As I have to "maximize the throughput of the combined 5L and 10L production line while taking into account the use of resources", I will determine the lowest buffer capacity that is needed to reach a fixed average throughput.

I have performed experiments with the buffer sizes, under 'normal circumstances', meaning that the experiments are conducted in Situation 1, using no production line optimization technique.

When conducting the experiments with buffer capacities of both 200 cans for the buffer in front of the bottleneck (from now on called buffer A) and the buffer behind the bottleneck (from now on called buffer B), the utilizations were 17.21% and 8.43% respectively. This gives an average usage of about 35 cans and 15 cans respectively. I will experiment with this average usage, by multiplying the average usage with 1, 2, 3, 4, 5, and 6, respectively. Thus, when using a multiplication factor of 6, the buffer capacities will be 210 and 90, respectively.

I will not conduct experiments with the 10L production scheme, as buffering will not increase the average throughput regarding a 10L production scheme, as described in Section 6.3.5.

The results from the experiments are depicted in Figure 6.10. This figure shows that the average throughput is fairly constant until a multiplication factor of 3, but starts to increase from that point. With a significance level of 95%, it can be shown that only using a multiplication factor of 6, representing a buffer space of 210 5L cans in front of the filler capper and 90 5L cans behind the filler capper, will increase the average throughput, when comparing the average throughput to the average throughput of using multiplication factor 1.

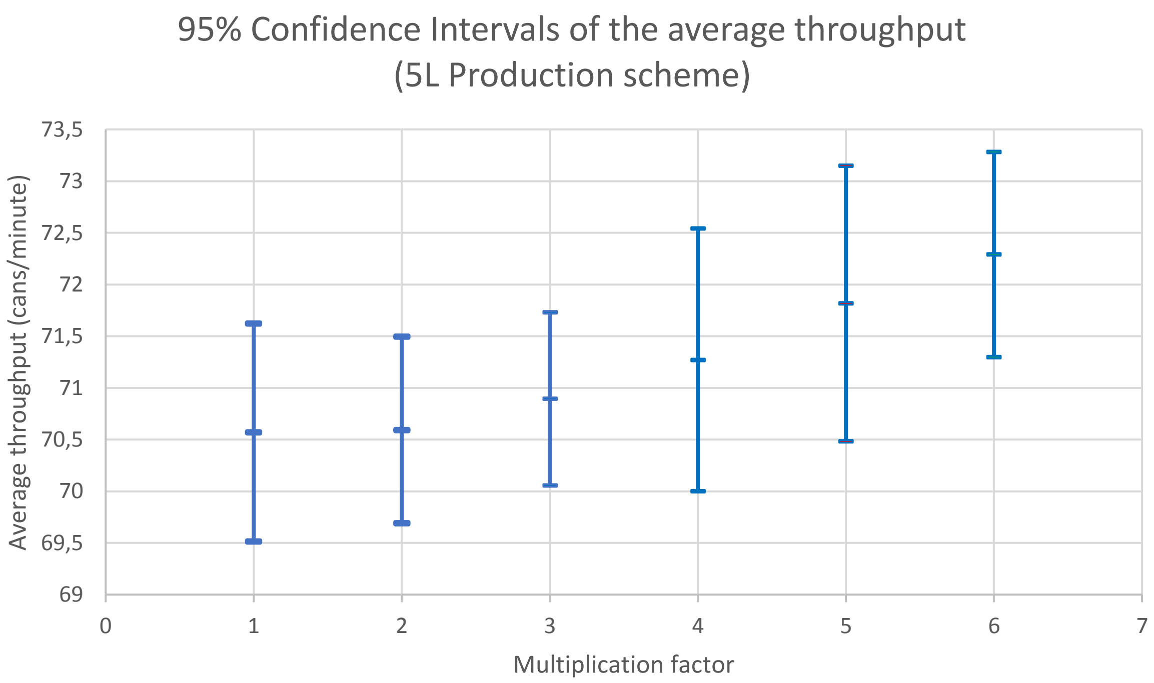


Figure 6.10 | 95% Confidence intervals regarding the average throughput of the 5L production scheme (cans/minute)

6.5 The influence of variability on the simulation output

In this section, the influence of variability on the simulation output is discussed. As the trends in each situation in the experiments conducted in Sections 6.3.4 and 6.3.5 seems to be the same, I tested how the output would look like in case a lot of replications (100) are conducted.

I have created 95% confidence intervals of the OEE and the average throughput of both the 5L and 10L production scheme, which are depicted in figure A6.1 in Appendix 6. The situation for which these intervals are created is the situation in which no production line optimization technique is used. These figures show interesting results, as the confidence intervals in each figure are almost identical.

- The 95% confidence intervals of the OEE regarding the 5L production scheme are in the range between 25.8% and 26.7%, which is a very small interval as the width of this interval is 1.7% relative to the mean.
- The 95% confidence intervals of the average throughput regarding the 5L production scheme are in the range between 69.2 cans/minute and 70.7 cans/minute, which is also a very small interval as the width of this interval is 1.1% relative to the mean.
- The 95% confidence intervals of the OEE regarding the 10L production scheme are in the range between 31.1% and 32.0%, which is also very small interval as the width of this interval is 1.4% relative to the mean.
- The 95% confidence intervals of the average throughput regarding the 10L production scheme are in the range between 44.3 cans/minute and 45.0 cans/minute, which is also a very small interval as the width of this interval is 0.8% relative to the mean.

Because all those intervals are really small, this means that the degree of variability in the DeviationPercentageMTTF and DeviationPercentageMTTR does not influence the values of the OEE and the average throughput.

Therefore, it is possible to create a deterministic model of the production line that can give accurate approximations of the average throughput of the production line. I have therefore created a deterministic model of the production line to approximate the average throughput of the production line, which is described in Chapter 7. This deterministic model is created for the situation in which no production line optimization technique is used.

7 Deterministic model of the production line

In this chapter, I created a deterministic model of the production line to estimate the average throughput. This deterministic model is created for the situation in which no production line optimization technique is used. This chapter is structured as follows:

- Section 7.1 explains the deterministic model.
- Section 7.2 describes how the deterministic model is used for each product type.
- Section 7.3 describes the outcomes of the deterministic model.
- Section 7.4 compares the outcomes of the deterministic model with the outcomes of the simulation model.

7.1 Explanation of the deterministic model

At first, the variables used in my deterministic model of the production line are explained. These variables are listed below:

- A_i = availability of workstation i
- A_{PL} = availability of the production line
- AverageThroughput = Average throughput of the production line (cans/minute)
- AvgTP = Average throughput of the production line in steady state (cans/minute)
- BatchSize = Batch size of the production scheme (2000 for 5L and 1000 for 10L)
- $CycleTime_i$ = Workstation cycle time of workstation i (s)
- D_n = conveyor belt length from the first workstation till the last workstation n (m)
- LineSpeed = the speed of the conveyor belts (m/s)
- $MTTF_i$ = Mean Time To Failure of workstation i (minutes)
- $MTTR_i$ = Mean Time To Repair of workstation i (minutes)
- $ProcSize_i$ = Processing size of workstation i
- $ProcSpeed_B$ = Processing speed of the bottleneck (cans/minute)
- $ProcSpeed_i$ = Processing speed of workstation i (cans/minute)
- TBT = total time that is needed to produce a batch (s)
- TTST = the time till the production line reaches its steady state (s)

The first step to calculate the average throughput of the production is to calculate the availability of each workstation i by the following formula (Slack, Chambers, & Johnston, 2010, p. 582):

$$A_i = \frac{MTTF_i}{MTTF_i + MTTR_i}$$

After that, the availability of the production line can be calculated by taking the product of the availabilities of all the workstations, as it is a serial production line:

$$A_{PL} = \prod_{i=1}^{n} A_i$$

Now that the availability of the production line is calculated, the average throughput when the production line is in steady state can be calculated. As the processing speed of the bottleneck determines the throughput of the production line, the average throughput of the production line in steady state can be calculated by using the formula:

$$AvgTP = A_{PL} \times ProcSpeed_B = A_{PL} \times \min\{ProcSpeed_1, \dots, ProcSpeed_n\}$$

Note that the average throughput (AvgTP) is reached in steady state. The time till the steady state can also be calculated, as this the time that the first can enters the last workstation in the production line. Each can spends a certain time in each workstation, called the workstation cycle time ($CycleTime_i$), of which the formula is shown in Section 4.2.2, and is transported over the conveyor belt. Thus, the time till the first can enters the last workstation (workstation n) is the total time that a can spends in workstation 1 till n-1 and the total time on the conveyor belt from the first workstation till the last workstation (the box labeler for the 5L cans and the labeler for the 10L cans). The time till the steady state can thus be calculated using the formula:

$$TTST = \frac{D_n}{LineSpeed} + \sum_{i=1}^{n-1} CycleTime_i = \frac{D_n}{LineSpeed} + \sum_{i=1}^{n-1} \frac{60}{ProcSpeed_i} \times ProcSize_i$$

Now that the time till the steady state and the average throughput in steady state are calculated, the total time that is needed to produce a batch can be calculated, using the following formula:

$$TBT = TTST + \frac{BatchSize}{\frac{AvgTP}{60}}$$

Now that the total time to produce a batch is calculated, the average throughput can be calculated, using the following formula:

$$AverageThroughput = \frac{BatchSize}{\frac{TBT}{60}}$$

7.2 The use of the deterministic model for each product type

For each of the five product types described in Section 2.1.3, a separate production line is created, because each product type has a different product route. Thus, for each product type, a separate deterministic model is created. All the workstations that do not process the product for a specific product type are excluded from the production line. Take for example 5L_Type1: for this product type, a production line is created containing all the workstations, except the labeler. For 10L_Type2, a production line is created containing only the depalletizer, the sleever and the filler capper. Next to that, the box erector is not taken into account for each deterministic model, as no cans visit the box erector.

7.3 Outcomes of the deterministic model

For each of the five product types described in Section 2.1.3, the average throughput of a batch of this product type is calculated. These results are presented in Table 7.1 below. For the product 5L_Type1, an example calculation of the average throughput is shown in Appendix 7.

Product type	Average throughput (cans/minute)
5L_Type1	63.6
5L_Type2	69.2
10L_Type1	41.7
10L_Type2	45.6
10L_Type 3	38.3

Table 7.1 | Average throughput for each product type (cans/minute)

With this information, the average throughput of both production schemes can be calculated. As the 5L production scheme consists of 6 5L_Type1 batches and 7 5L_Type2 batches, the average throughput (in cans/minute) of the 5L production scheme can be calculated as follows:

$$Average\ throughput\ 5L\ production\ scheme = \frac{6 \times 63.6 + 7 \times 69.2}{6 + 7} \approx 66.6$$

As the 10L production scheme consists out of 5 10L_Type1 batches, 4 10L_Type2 batches, and 4 10L_Type3 batches, the average throughput (in cans/minute) of the 10L production scheme can be calculated as follows:

$$Average\ throughput\ 10L\ production\ scheme = \frac{5 \times 41.7 + 4 \times 45.6 + 4 \times 38.3}{5 + 4 + 4} \approx 41.9$$

7.4 Comparison between the deterministic model and the simulation model

When comparing the outcomes of the deterministic model and the simulation model, the difference between the two models is quite small, meaning that the deterministic model can approximate the output of the simulation model very well.

The average throughput of the 5L production scheme is, according to the simulation model, about 70 cans/minute, as described in Section 6.5. The average throughput of the 5L production scheme is, according to the deterministic model, 66.6 cans/minute. Thus, the difference between the deterministic model and the simulation model is 4.79%.

The average throughput of the 10L production scheme is, according to the simulation model, about 45 cans/minute, as described in Section 6.5. The average throughput of the 5L production scheme is, according to the deterministic model, 41.9 cans/minute. Thus, the difference between the deterministic model and the simulation model is 6.97%.

The average throughput according to the deterministic model is slightly lower, as the batch changing time is excluded in this model. In the simulation model, it is possible that a workstation fails in the batch changing time, which does not affect the average throughput. In the deterministic model, the workstation can only fail during production time, therefore the average throughput is lower in this model.

8 Conclusion, recommendations and discussion

In this chapter, I will conclude on the experiments that are conducted in Chapter 6. This will also include a recap of the problem statement in terms of a norm and reality, which is described in Section 1.4. Next to that, I will present my recommendations to Company X in terms of the parametrization of the production line and I will give additional recommendations regarding data collection and the continuation of my bachelor thesis and models. This chapter closes with a critical discussion on my bachelor thesis, as there are some limitations that might have influenced the accuracy of my simulation model. This chapter is structured as follows:

- Section 8.1 concludes on the experiments conducted in Chapter 6.
- Section 8.2 gives recommendations to Company X.
- Section 8.3 critically discusses my bachelor thesis.

8.1 Conclusion

The conclusion is divided into three different sub-sections: a conclusion on the production line optimization techniques, a conclusion on the buffer space needed for the box erector, and a conclusion on the processing speed of the depalletizer.

8.1.1 Conclusion on production line optimization techniques

When analyzing the results from the experiments in Section 6.3.4 regarding the 5L production scheme, it shows that only buffering in front of the bottleneck and behind the bottleneck will increase the average throughput and the OEE. Additional experiments with the buffer sizes in Section 6.4.3 showed that only a buffer of 210 5L cans in front of the filler capper and a buffer of 90 5L cans behind the filler capper would increase the average throughput.

When analyzing the results from the experiments in Section 6.3.5 regarding the 10L production scheme, it shows that there is no production line optimization technique that increases the average throughput or the OEE.

When looking back at the problem statement in terms of a norm and reality, which is described in Section 1.4, Company X can realize a maximum average throughput of either 70 5L cans per minute or 45 10L cans per minute without the use of any production line optimization technique.

8.1.2 Conclusion on the buffer space needed for the box erector

When analyzing the results from the experiments regarding the buffer space that is needed for the box erector, presented in Section 6.4.1, the current estimated average time between the filling of the buffer, which is about 5 minutes according to the operators, can be reached with a buffer space of two meters. The workstation that is expected to be bought, which accommodates 4 meters of buffer space, will result in an average time between the filling of the buffer of around 10 minutes.

8.1.3 Conclusion on the processing speed of the depalletizer

When analyzing the results from the experiments regarding the processing speed of the depalletizer, presented in Section 6.4.2, it shows that the depalletizer is indeed not the bottleneck, as increasing the processing speed of the depalletizer does not lead to big increases in the average throughput. The throughput is only increased in case of a processing speed of 120 cans per minute regarding the 5L production scheme, but this increase in throughput is only 2.27% and probably was an outlier, having very favorable random number streams, as described in Section 6.4.2.

8.2 Recommendations

The recommendations are divided into five different sub-sections: a recommendation on the production line optimization techniques, a recommendation on the buffer space of the box erector, a recommendation on the processing speed of the depalletizer, a recommendation regarding data collection, and a recommendation on the continuation on my bachelor thesis and models.

8.2.1 Recommendation on production line optimization techniques

As only a buffer space of 210 5L cans in front of the filler capper and 90 5L cans behind the filler capper will increase the average throughput and the OEE, Company X should not use this optimization technique. A buffer space of 210 or 90 5L cans is unfeasible, as it costs a lot of money to purchase a buffer station and it will need a lot of space. The space in front of the filler capper is very limited as can be seen in Figure 4.2. It is very crowded as the filler capper is a large workstation, the sleever is near the filler capper, and another production line is situated next to the filler capper. Next to that, there is no production line optimization technique that increases the average throughput or the OEE regarding the 10L production scheme.

Thus, Company X should not make use of a production line optimization technique, as buffering in front of the bottleneck and behind the bottleneck is too expensive, takes too much space and will not increase the average throughput and OEE when finishing a 10L production scheme.

8.2.2 Recommendation on the buffer space for the box erector

As the current estimated average time between the filling of the buffer is about 5 minutes, the workstation that is expected to be bought will double the average time between the filling of the buffer. As the operators stated that an interval of 5 minutes is perfectly feasible, I recommend Company X to purchase the workstation that is the current candidate, which accommodates 4 meters of buffer space, as this will create even better working conditions for the operators.

8.2.3 Recommendation on the processing speed of the depalletizer

As the depalletizer was indeed not the bottleneck in the production line, I advise Company X not to buy a depalletizer with a processing speed higher than 100 5L cans or 60 10L cans per minute, as the experiments have shown that increasing the processing speed does not increase the average throughput or the OEE.

8.2.4 Recommendation regarding data collection

Another recommendation that I can give to Company X is to collect data about the production line. Collecting data about the production line is very important for the following reason: data can be used for future analyses of the production line. Data about batch changing times and failure data can be collected to provide a more accurate simulation model.

The failure data should be collected in the following way: the operators should specify different types of failures. The sleever can, for example, have two types of failures: a type A failure means that the sleeves have to be replaced for new sleeves, and a type B failure means that the sleever suffices from a malfunction. After having determined which type of failure has occurred, the operator should denote the starting time of the failure and the end time of the failure, which can be used to create statistical distributions for the Time To Failures and the Time To Repair.

The data regarding batch changing times should be collected in the same way: the operators should specify the product from the current batch. After that, the operators should denote the starting time of the batch changing process and the end time of the batch changing process. After having collected a lot of these data points, a product dependent batch changing time distribution can be created, providing more accurate simulation results.

8.2.5 Recommendation on the continuation of my bachelor thesis and models

I recommend Company X to update my simulation model in case the production line does not perform as expected or when the production line does not seem to be balanced. The simulation model can then be updated if there is enough data collected about the production line. Of course, the data should be collected when the new production line is fully operational and the start-up phase of the new production line is over. In case Company X wants to update the simulation model, I recommend Company X to update the simulation after half a year of data is collected.

A more accurate simulation model might provide useful insights into the production line, which might help to increase the performance of the production line, for example by using a production line optimization technique mentioned in this bachelor thesis. Next to that, new production line optimization techniques can be tested by means of a simulation study.

When Company X is not able to work with the simulation model, I advise them to update and to further develop the deterministic model of the production line. This deterministic model might also help Company X to estimate the average throughput that can be acquired by replacing certain workstations.

8.3 Discussion

The discussion is divided into three different sub-sections: a discussion on the lack of data, a discussion on the overestimations of the average throughput and an underestimation of the OEE, and a discussion of the validation of the simulation model.

8.3.1 Lack of data

As there was little data available about the production line, it was hard to create batch changing time distributions and failure distributions. To cope with this, I have conducted sensitivity analyses with the statistical distributions to correct for inadequate representations of the real world, which is described in Section 6.2.1. Due to the limited time of ten weeks that were available to conduct my bachelor assignment, I did not have the opportunity to collect enough data about the production line.

The sensitivity analyses gave roughly the same output, as shown in Section 6.5, meaning that the variability did not really affect the simulation model. However, the output of the simulation model would have been a lot more accurate if I had a lot of data about batch changing times and failures.

8.3.2 Overestimations of the average throughput and underestimation of the OEE

As I have excluded two workstations, the track and trace labeler and the palletizer, as described in Section 4.1.2 and Section 4.1.1 respectively, I have overestimated the average throughput. As both workstations are not modeled, both workstations are assumed to have an infinite processing speed and both workstations cannot fail. When the workstations do not have an infinite processing speed and the workstations can fail, this can bring down the average throughput. The OEE is underestimated in my simulation model, because of the unrealistic target throughput values of 100 5L cans/minute and 60 10L cans/minute; the OEE of the production line will thus be higher when there are realistic target throughput values.

8.3.3 Validation of the simulation model with real-world data

As the production line is not built yet, I was not able to validate my simulation model with real-world data. However, I have validated my simulation model as much as possible by means of an expert opinion and a comparison with a deterministic model and I have looked through all the code with my supervisor at Company X to detect any errors. As the expert opinion of my supervisor and the calculations from the deterministic model of the production line were very close to the performance of my simulation model and we could not find any mistakes in my simulation model, we considered my simulation model to be correctly validated.

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Appendix 1 Detailed time schedule of a batch changing process

In this appendix, I will present a detailed time schedule of the batch changing process, as described in Section 2.3. I observed a batch changing process performed by two operators of Company X. This batch changing process took place on the current 5L production line.

In Figure A1.1, I have created a schedule of all the operations that were performed during that batch changing process. The start time and the end time of an operation are depicted and a list of operations is presented. Next to that, it can be seen which operator performed an operation.

The first operation, operation A, was the end of the last batch, which was making sure that an even number of cans was filled. If this is not the case, one box will only contain one can, which is not the intention. This checking took place by the two operators, who both checked one part of production line.

After that, the draining of the filler capper was activated and the filler capper was cleaned. The other operator changed the sleeves and checked whether the sleeves were applied correctly to the next batch. After that, the second operator helped cleaning the filler capper.

Right now, the second operator leaves and the other operator sets the print code for the labeler, changed the labels and set the right code for the track and trace labeler. After setting the right code for the track and trace labeler, the operator set the labels for the box labeler and checked whether the labels were applied correctly.

After that, the operator completely drained the pipes and filled them directly after. This is the beginning of the new batch. The operator now checks the first cans from the new batch regarding their weight and concentration. After that, the operator checks some additional cans from the new batch.

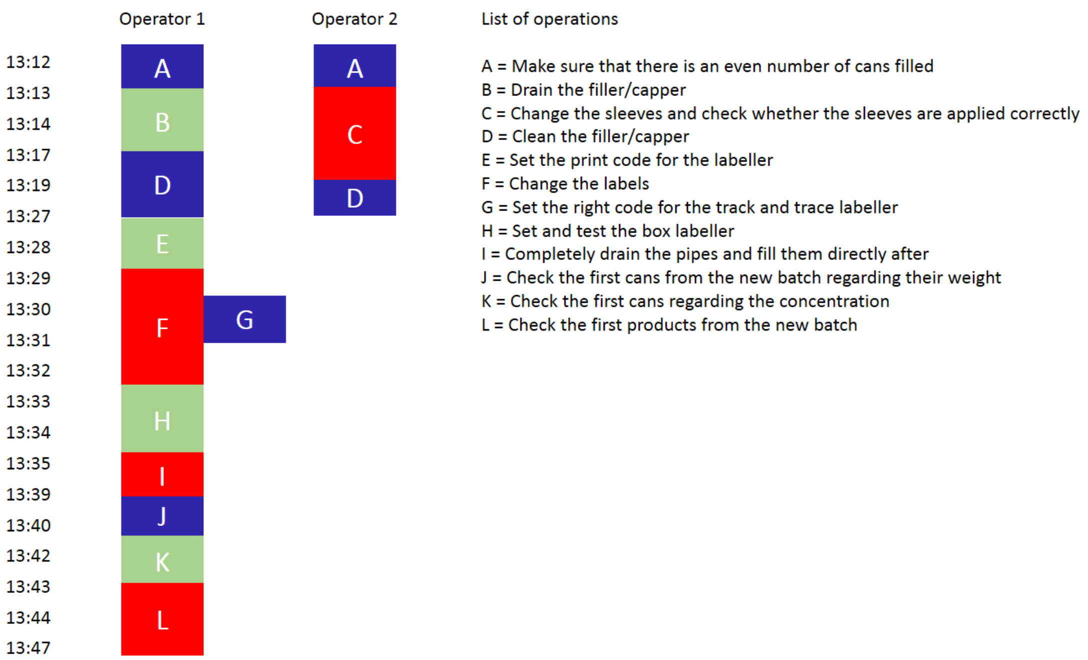

Figure A1.1 | Detailed time schedule of a batch changing process

Appendix 2 Systematic Literature Review protocol

In this appendix, I will present my systematic literature review protocol that I used for my Systematic Literature Review of which the result is presented in Section 3.3. The Systematic Literature Review is structured as follows, based on Löwik (2018):

1. Theoretical perspective and the key theoretical concepts (Section A2.1)
2. Define search strings (Section A2.2)
3. Determine inclusion and exclusion criteria (Section A2.3)
4. Present an overview of the searching and filtering process (Section A2.4)
5. Use a conceptual matrix (Section A2.5)
6. Final list of sources that I used for the Systematic Literature Review (Section A2.6)

A2.1 Theoretical perspective and key theoretical concepts

My theoretical perspective is defined as follows: I will look at bottlenecks in production lines from an angle of approach of Operations Research and Operations Management. In most production lines, the workstations are not perfectly balanced, meaning that not the same amount of work is loaded onto each separate workstation. This means that there is likely to be a bottleneck in the process, a workstation that limits the throughput of the production line.

In the literature, there are methodologies that can be used to improve the performance of the production line by optimizing bottlenecks. One of those methodologies is OPT, also known as Optimized Production Technology, which states that bottlenecks determine the throughput of the production line (Goldratt & Cox, Het doel: Een proces van voortdurende verbetering, 1988, p. 283). Another methodology is the TOC, also known as the Theory of Constraints, which is a methodology that iteratively improves the performance of a production line by exploiting the constraints (Goldratt, Theory of Constraints, 1999). The DBR methodology, also known as the Drum-Buffer-Rope methodology comes from the Theory of Constraints and the Optimized Production Technology. The DBR methodology helps to decide exactly where in a process control should occur, because the amount of work loaded onto each workstation in the production line is often not perfectly balanced (Slack, Chambers, & Johnston, 2010, p. 290).

With this systematic literature review, I want to find more information about those three production line optimization methodologies, in terms of theory explanation and case studies. So, the knowledge problem that I want to answer by means of this systematic literature review is:

"What production line optimization methodologies exist in the literature and how are they applied in practice?"

I will look for qualitative literature about production line optimization methodologies; I will not focus on quantitative optimization techniques, as I will use a textbook for that.

A2.2 Define search strings

To find relevant articles which will help to find the information described in Section A2.1, I have to make smart use of search strings. Therefore, I made sure I used very specific search strings to exclude irrelevant articles that will not help me to answer my knowledge problem. Below, I will explain the search strings that I have used and why I used these search strings.

I used two types of search strings: fixed search strings and variable search strings. The fixed search strings are used in every search and one of the variable search strings is added to the fixed search strings.

The fixed search strings that I used are "bottleneck" and "production". An explanation of the use of these search strings is presented below.

1. **Bottleneck:** I want to find theory about methodologies that are based on the optimization of bottlenecks. This search string will make sure that the correct methodologies (OPT, TOC and DBR) are selected and other theories with the same abbreviations are excluded.
2. **Production:** Using this search string will make sure that bottleneck optimization methodologies are selected in the context of a production environment. This will filter out bottleneck optimization methodologies in medical environments, for example.

The variable search strings that I used are "OPT", "TOC" and "DBR". An explanation of the use of these search strings is presented below.

1. **OPT:** I want to find information about the Optimized Production Technology (OPT) or theories derived from the OPT.
2. **TOC:** I want to find information about the Theory of Constraints (TOC) or theories derived from the TOC.
3. **DBR:** I want to find information about the Drum-Buffer-Rope methodology (DBR) or theories derived from the DBR.

I have chosen to conduct my systematic literature review in two databases: Scopus and Web of Science. Articles from both databases will be integrated and checked on overlaps.

A2.3 Inclusion and exclusion criteria

In this section, I will present my inclusion and exclusion criteria that I used to filter the articles that I want to read for my systematic literature review. In Section A2.3.1, I will present my inclusion criteria and in Section A2.3.2, I will present my exclusion criteria.

A2.3.1 Inclusion criteria

The inclusion criteria that I used to filter out articles that I want to read are presented in Table A2.1 below, including a motivation for the use of these specific inclusion criteria.

Number	Inclusion criterion	Reason for inclusion
1	Explanations on theory of Optimized Production Technology, Theory of Constraints or Drum-Buffer-Rope methodology	I want to find explanations of the different methodologies (OPT, TOC or DBR), such that I can get a better insight into the principles of those methodologies. This will make me more acquainted with the theory, such that I can more easily apply it to my bachelor assignment.
2	Case studies on Optimized Production Technology, Theory of Constraints or Drum-Buffer-Rope methodology	I want to find applications for the different methodologies (OPT, TOC or DBR) in terms of case studies. Case studies will namely confirm or criticize these methodologies, which will help me to identify the advantages and disadvantages of the theories when applied in practice.

Table A2.1 | Inclusion criteria

A2.3.2 Exclusion criteria

The exclusion criteria that I used to filter out articles that I do not want to read are presented in Table A2.2 below, including a motivation for the use of these specific exclusion criteria.

Number	Exclusion criterion	Reason for exclusion
1	Articles released earlier than 2010 with less than 10 citations	The number of citations is a measure of the quality of an article. If the article is released earlier than 2010, such that the article could have been cited a lot now, and has less than 10 citations, this means that the quality of the article is not that good.
2	Articles released earlier than 2015 with no citations	The number of citations is a measure of the quality of an article. If the article is released earlier than 2015 and the quality of the article is good, it should have been cited at least once. Therefore, I want to exclude the articles with a not so good quality, by filtering on this exclusion criterion.
3	Articles released earlier than 2014 that are published in journals with an impact factor lower than 2	The impact factor of a journal determines the quality of the journal and with that, the quality of the articles. Articles that are released earlier than 2014 ensure that the journal exists for 5 years now. If the journal then has an impact factor lower than 2, this means that the quality of the journal is not that good.
4	Articles with another context than a production line environment	Articles with another context than a production environment context should be excluded, for example articles with a medical context or articles about product-mix decisions. These articles do not fit the context of my assignment, as I only want to focus on production line environments.
5	Proceedings	I will exclude proceedings, as I do not know how these proceedings for conferences are judged. Therefore, I cannot guarantee the quality of the article. Based on this, I decided to exclude all proceedings.
6	Articles that are not written in English	I will exclude articles that are not written in English, as I cannot understand Spanish or Chinese articles (which I encountered), for example.
7	Articles that only focus on the identification of bottlenecks	I will exclude articles that only focus on the identification of bottlenecks, as I want to collect information on how to optimize a production line by optimizing bottlenecks. The optimization methodology is missing in these types of articles.
8	Articles that do not focus on the optimization methodologies	I will exclude articles that do not focus on the optimization methodologies. I want to collect information about the methodologies or the application thereof, not only about mathematical models, for example.
9	Articles that are not accessible	I have excluded articles that are not accessible, for example articles for which I have to pay or articles that only publish the abstracts.

Table A2.2 | Exclusion criteria

A2.4 Overview of the searching process

In this section, I will present an overview of the searching process, which shows the application of the search strings, the inclusion criteria and the exclusion criteria. This overview is presented in Table A2.3 below. Note that I included two books after conducting my filtering process with articles. Those two books are named ‘source 6’ and ‘source 7’ in Section A2.6.

Search string	Scope	Date of search	Number of entries
Search protocol for Scopus			
“bottleneck” AND “production” AND “OPT”	Article title, Abstract, Keywords	10 April 2018	24
“bottleneck” AND “production” AND “TOC”	Article title, Abstract, Keywords	10 April 2018	84
“bottleneck” AND “production” AND “DBR”	Article title, Abstract, Keywords	10 April 2018	27
Search protocol for Web of Science			
“bottleneck” AND “production” AND “OPT”	Topic	10 April 2018	12
“bottleneck” AND “production” AND “TOC”	Topic	10 April 2018	59
“bottleneck” AND “production” AND “DBR”	Topic	10 April 2018	21
Total number of articles in list			**227**
Remove duplicates			-79
Selecting based on exclusion criteria			-140
Removed after reading complete article			-3
Books included			+2
Sources used			**7**

Table A2.3 | Overview of the searching process

A2.5 Overview of the conceptual matrix

In this section, I will present the conceptual matrix that I used to categorize the information that I have acquired from reading the articles and the books for my systematic literature review. The conceptual matrix is presented in Table A2.4 below. Note that the source is depicted with a number. In Section A2.6, a list of sources used is presented, in which the type of source, the title, (the journal), and the authors for each source are listed.

	OPT		TOC		DBR	
Source number	**Theory**	**Case study**	**Theory**	**Case study**	**Theory**	**Case study**
1				X		X
2				X		
3		X				
4				X		X
5						X
6	X					
7	X		X		X	

Table A2.4 | Conceptual matrix

A2.6 List of sources used for the systematic literature review

Source 1
Source type: article
Article title: A research on problems of mixed-line production and the re-scheduling
Journal: Robotics and Computer-Integrated Manufacturing
Authors: Hsiang-His Huang, Wen Pei, Horng-Huei Wu and Ming-Der May

Source 2
Source type: article
Article title: Bottleneck management: theory and practice
Journal: Production Planning & Control
Authors: S.S. Chakravorty and J. Brian Atwater

Source 3
Source type: article
Article title: Capacity planning in MRP, JIT and OPT: A critique
Journal: Engineering Costs and Production Economics
Authors: Ludo F. Gelders and Luk N. Van Wassenhove

Source 4
Source type: article
Article title: A study of the utilization of capacity constrained resources in drum-buffer-rope systems
Journal: Production and Operations Management
Authors: J. Brian Atwater and Satya S. Chakravorty

Source 5
Source type: article
Article title: Drum-buffer-rope and workload control in High-variety flow and job shops with bottlenecks: An assessment by simulation
Journal: International Journal of Production Economics
Authors: Matthias Thürer, Mark Stevenson, Cristovao Silva and Ting Qu

Source 6
Source type: book
Book title: Het doel: een proces van voortdurende verbetering
Authors: Eliyahu M. Goldratt and Jeff Cox

Source 7
Source type: book
Book title: Operations Management
Authors: Nigel Slack, Stuart Chambers and Robert Johnston

Appendix 3 Probability of three failures occurring at the same time

In this appendix, the probability of three failures occurring at the same time is calculated. For each of the workstations, the failure probability during the time interval between 28 and 32 minutes and during the time interval between 58 and 62 minutes is calculated. The time interval between 28 and 32 minutes is chosen according to the MTTFs of the depalletizer, sleever, labeler and the box labeler, which is 30 minutes; the time interval between 58 and 62 minutes is chosen according to the MTTF of the tape machine, which is 60 minutes.

The probability that the depalletizer fails at a time T between 28 and 32 minutes can be calculated as follows: $P(28 \leq T \leq 32) = e^{-\frac{1}{30}\times 28} - e^{-\frac{1}{30}\times 32} \approx 0.049$. The probability that the depalletizer fails at a time T between 58 and 60 is, following the same approach about 0.018.

The probability that the sleever fails at a time T between 28 and 32 minutes is equal to the probability that the labeler or the box labeler fails at a time T between 28 and 32 minutes, as they have the same probability distribution. This probability can be calculated as follows: $P(28 \leq T \leq 32) = \frac{4}{15} \approx 0.267$. This probability is about the same as the probability that one of the workstations fails at a time T between 58 and 62 minutes, as this as the MTTF to the second failure is 2 * 30 = 60 minutes.

As the probability distribution of the filler/capper, the box erector, and the packing machine are equal, the probability that one workstation fails at a time T between 28 and 32 minutes can be calculated as follows: $P(28 \leq T \leq 32) = e^{-\frac{1}{1440}\times 28} - e^{-\frac{1}{1440}\times 32} \approx 0.00027$, which can be neglected. With the same approach, the probability that one workstation fails at a time T between 58 and 62 minutes is about 0.00027, which can, again, be neglected.

The probability that the tape machine fails at a time T between 58 and 62 minutes can be calculated as follows: $P(58 \leq T \leq 62) = \frac{4}{30} \approx 0.133$.

Right now, the probability that at least three failures occur during the time interval between 28 and 32 minutes and during the time interval between 58 and 62 minutes can be calculated. The filler/capper, box erector, and the packing machine are excluded from this calculation, as their probability of failure during this interval can be neglected.

The probability that the sleever, labeler and the box labeler fail during at a time T between 28 and 32 minutes is $0.267^3 \approx 0.019$, taking into account that workstation failures are independent of each other. The probability that the depalletizer and two of the workstations of the sleever, labeler, and the box labeler fail at a time T between 28 and 32 minutes is $0.049 \times \binom{3}{2} \times 0.267^2 \approx 0.01$. Thus, the probability that three failures occur at a time T between 28 and 32 minutes is about 0.019 + 0.01 = 0.029 ≈ 3%.

The probability that the sleever, labeler and the box labeler fail during at a time T between 58 and 62 minutes is about 0.019. The probability that the depalletizer and two of workstations of the sleever, labeler, and the box labeler fail at a time T between 58 and 62 minutes is $0.018 \times \binom{3}{2} \times 0.267^2 \approx 0.00038$. The probability that the depalletizer, the tape machine and one of the workstations of the sleever, labeler, and the box labeler fail at a time T between 58 and 62 minutes is $0.018 \times 0.025 \times \binom{3}{1} \times 0.267 \approx 0.000036$. The probability that the tape machine and two of the workstations of the sleever, labeler, and the box labeler fail at a time T between 58 and 62 minutes is $0.025 \times \binom{3}{2} \times 0.267^2 \approx 0.00053$. Thus, the probability that three workstations fail at a time T between 58 and 62 minutes is about 0.019 + 0.00038 + 0.000036 + 0.00053 ≈ 0.020 = 2%.

Appendix 4 Conceptual process models of other product types

In this appendix, the conceptual process models from the other product types are presented. The conceptual process model from the production process of a 5L_Type2 product is presented in Figure A4.1, the conceptual process model from the production process of a 10L_Type1 product is presented in Figure A4.2, The conceptual process model from the production process of a 10L_Type2 product is presented in Figure A4.3, and the conceptual process model from the production process of a 10L_Type3 product is presented in Figure A4.4.

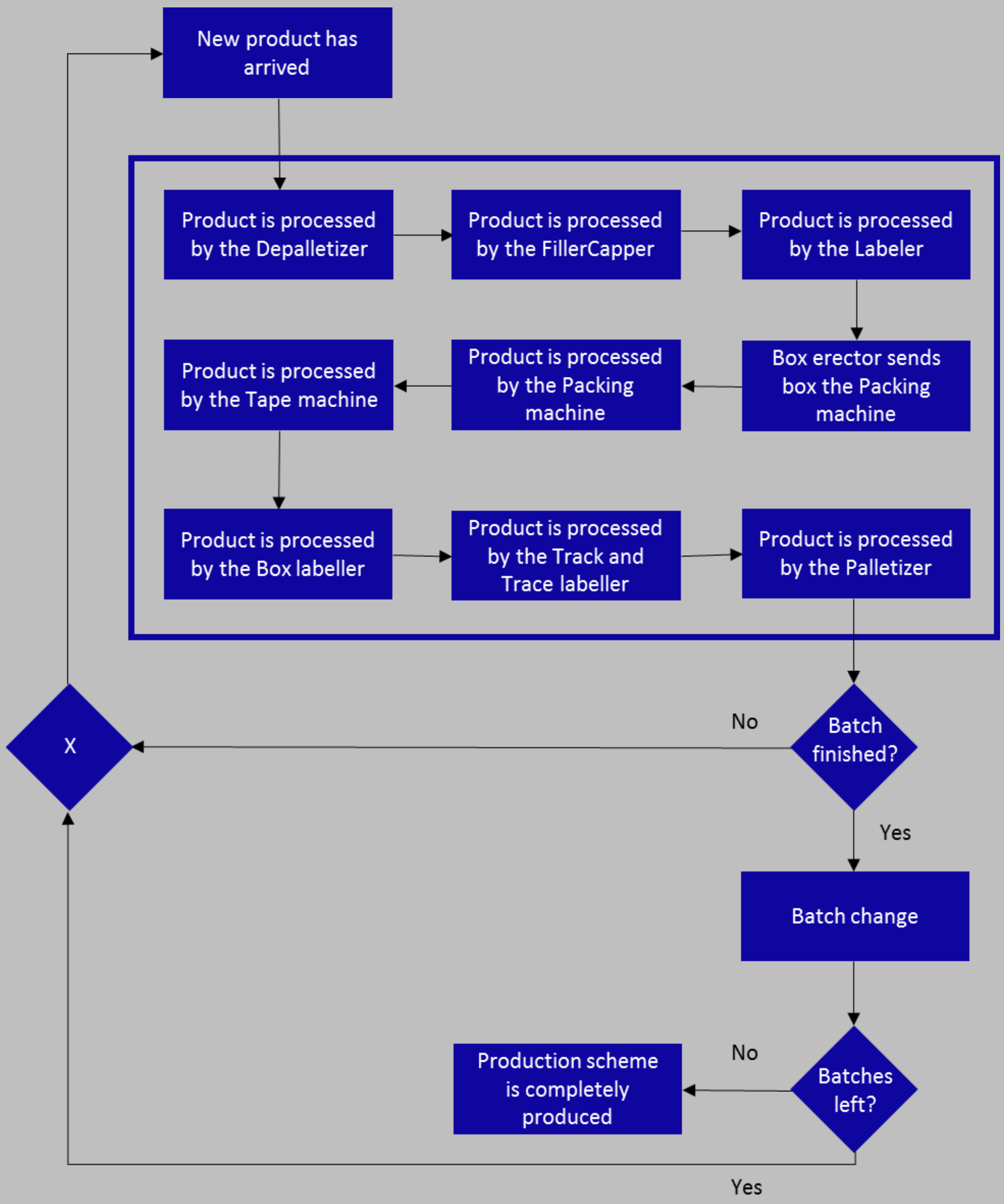

Figure A4.1 | Conceptual process model of a production process of a 5L_Type2 product

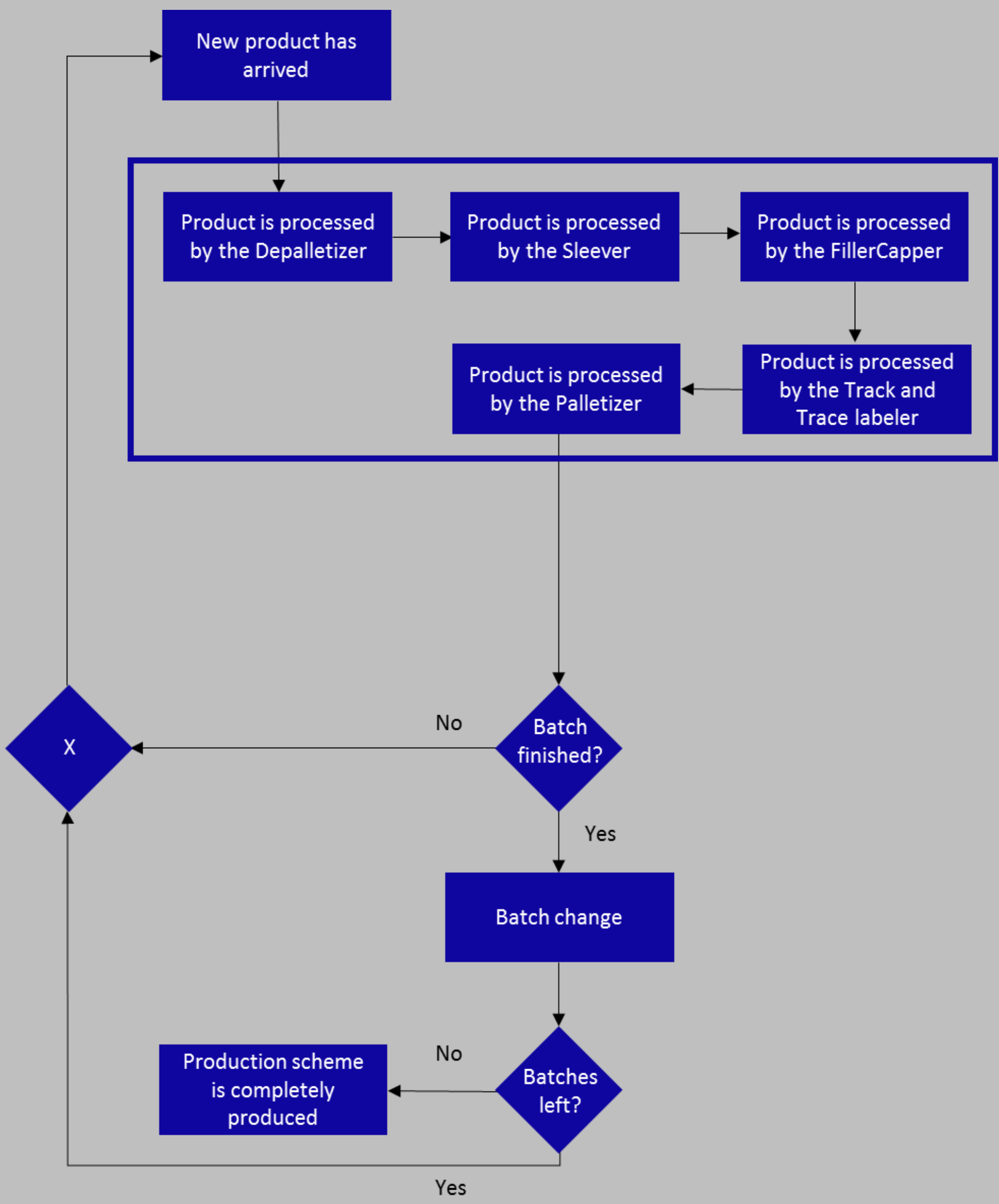

Figure A4.2 | Conceptual process model of a production process of a 10L_Type1 product

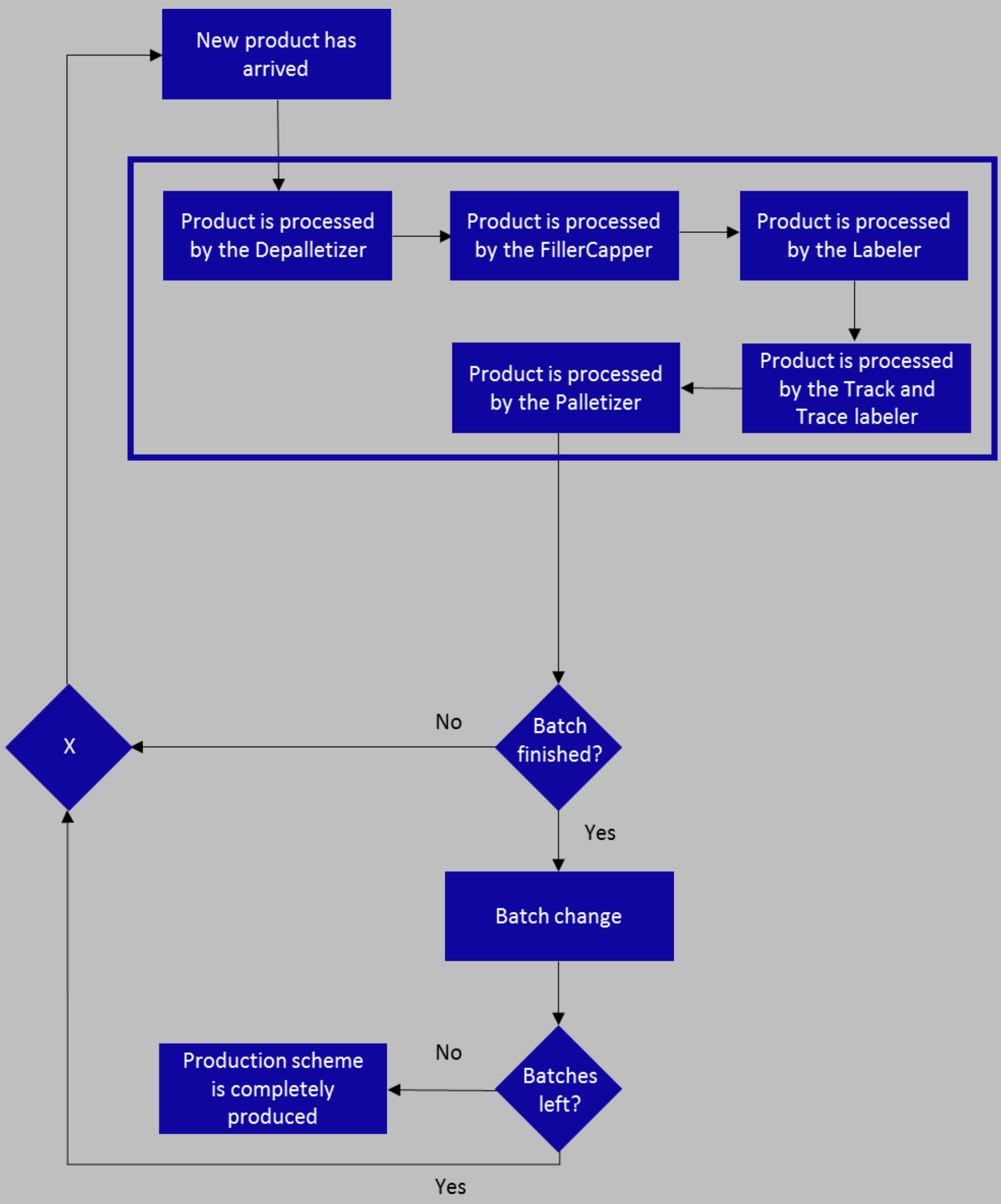

Figure A4.3 | Conceptual process model of a production process of a 10L_Type2 product

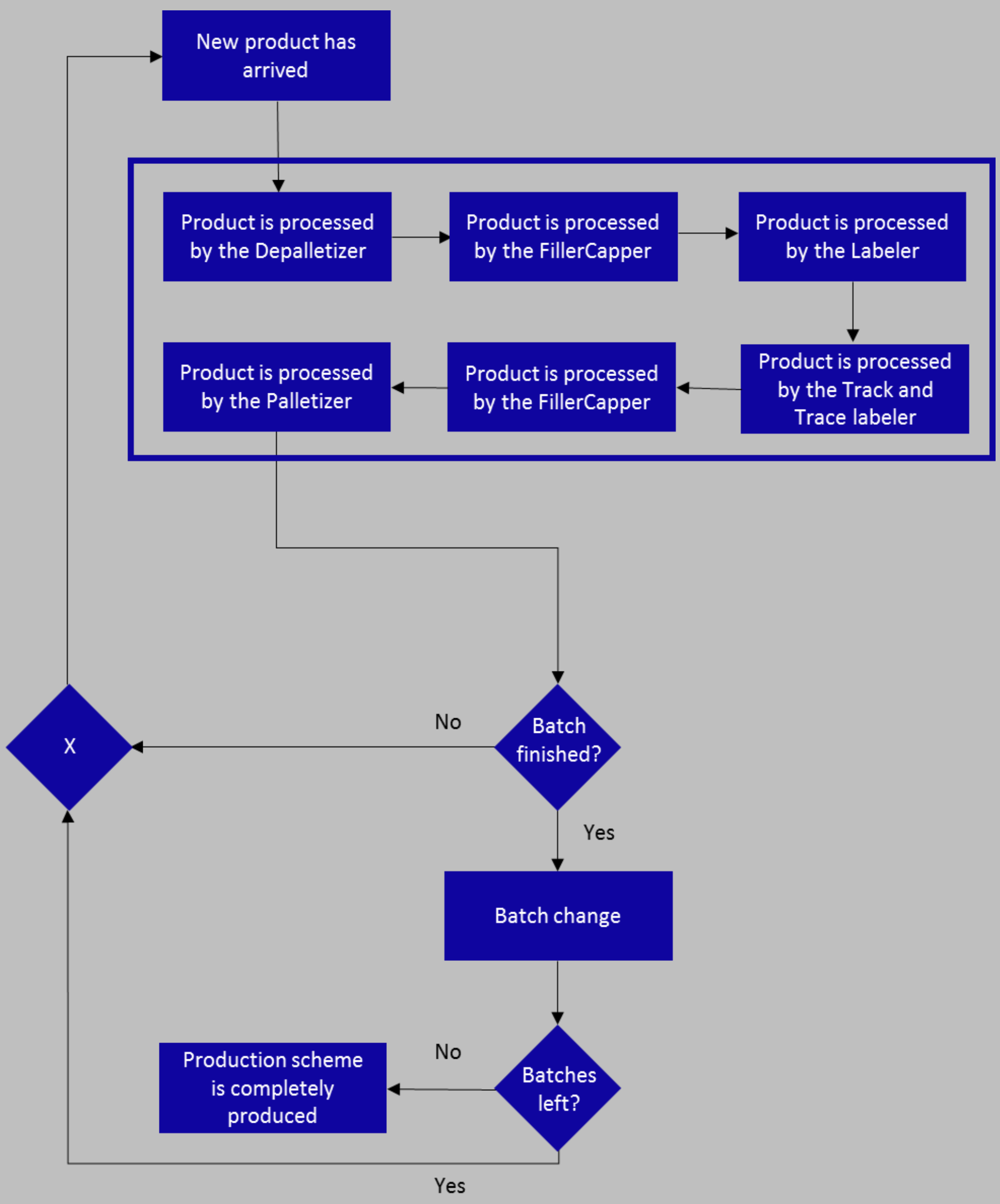

Figure A4.4 | Conceptual process model of a production process of a 10L_Type3 product

Appendix 5 Figures containing all data from the experiments

In this appendix, all the data from the experiments with production line optimization techniques regarding the 5L and 10L production scheme are presented. I have collected a lot of data with these experiments and I have created 95% confidence intervals regarding the OEE and the average throughput for all of the four situations described in Section 6.2.1.

The figures contain 20 confidence intervals. As can be seen, the confidence intervals are grouped in groups of five. Each group represents one of the four situations described in Section 6.2.1. Each group consists of five confidence intervals, numbered from (1) to (5), starting from the left.

- Confidence interval (1) represents the output for the current situation without optimization technique and is depicted in dark blue.
- Confidence interval (2) represents the output for the current situation with a buffer in front of the bottleneck and behind the bottleneck and is depicted in red.
- Confidence interval (3) represents the output for the V-curve principle and is depicted in green.
- Confidence interval (4) represents the output for the extended V-curve principle with operator activation and is depicted in yellow.
- Confidence interval (5) represents the output for the extended V-curve principle with automatic activation and is depicted in light blue.

This section contains four figures:

- Figure A5.1 presents the 95% confidence intervals regarding the OEE of the 5L production scheme.
- Figure A5.2 presents the 95% confidence intervals regarding the average throughput of the 5L production scheme.
- Figure A5.3 presents the 95% confidence intervals regarding the OEE of the 10L production scheme.
- Figure A5.4 presents the 95% confidence intervals regarding the average throughput of the 10L production scheme.

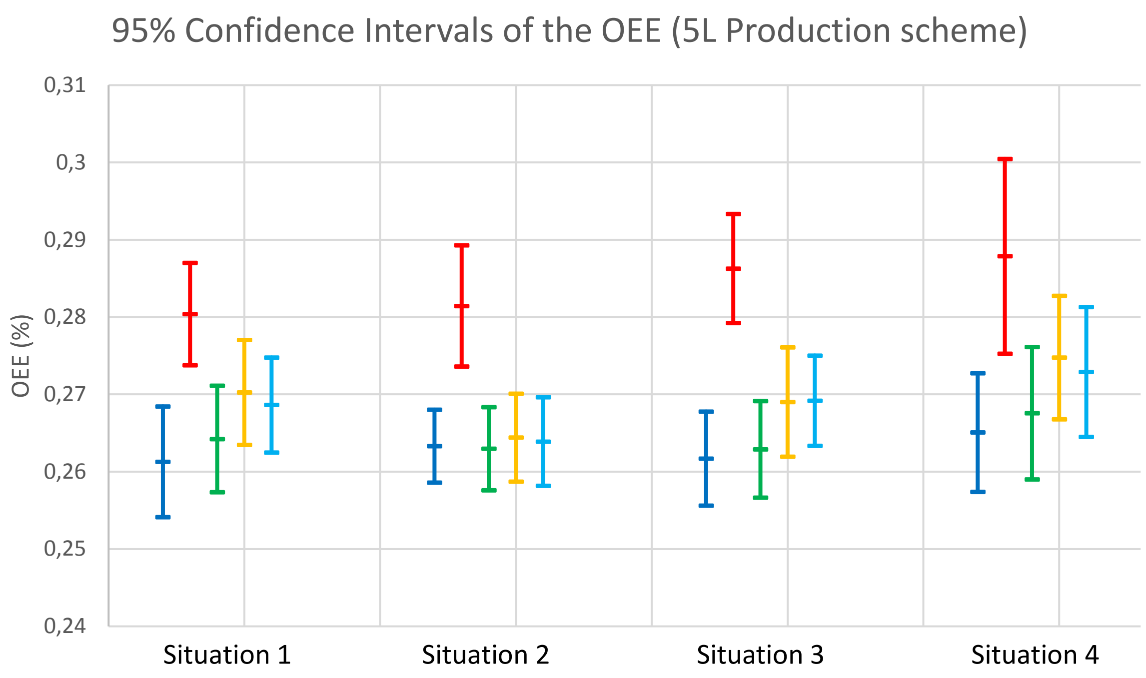

Figure A5.1 | 95% Confidence intervals regarding the OEE of the 5L production scheme (%)

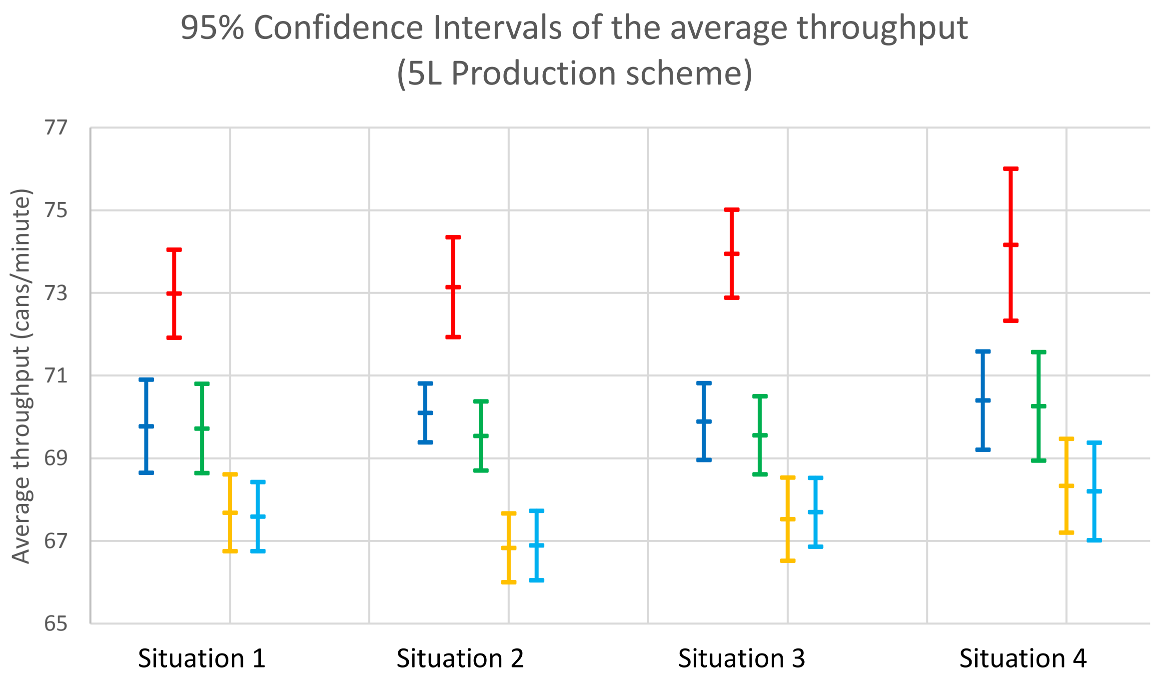

Figure A5.2 | 95% Confidence intervals regarding the average throughput of the 5L production scheme (cans/minute)

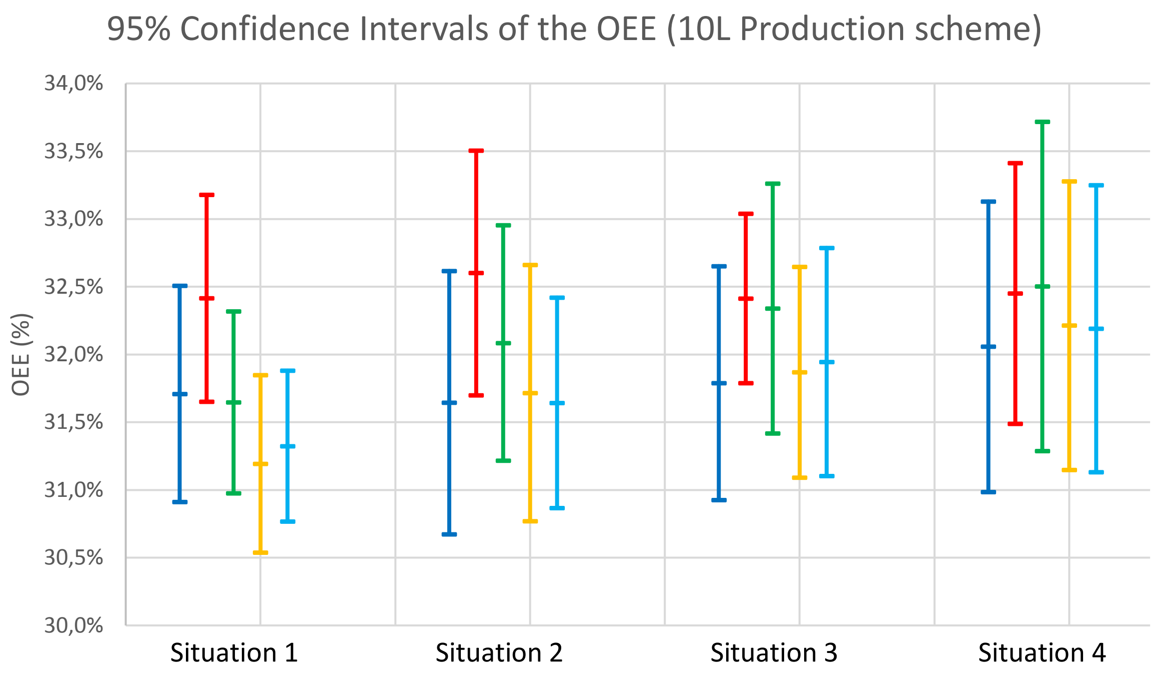

Figure A5.3 | 95% Confidence intervals regarding the OEE of the 10L production scheme (%)

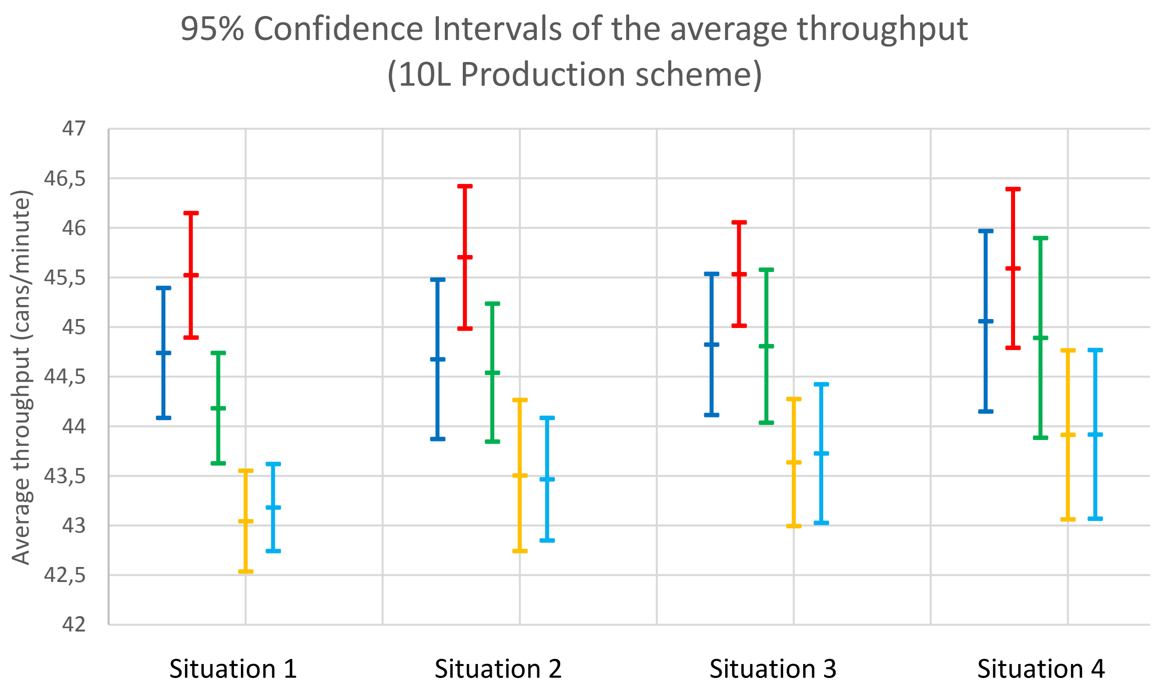

Figure A5.4 | 95% Confidence intervals regarding the average throughput of the 10L production scheme (cans/minute)

Appendix 6 Figures for the influence of the variability

In this appendix, the figure referred to in Section 6.5 are presented. I have created 95% confidence intervals of the OEE and the average throughput of both the 5L and 10L production scheme.

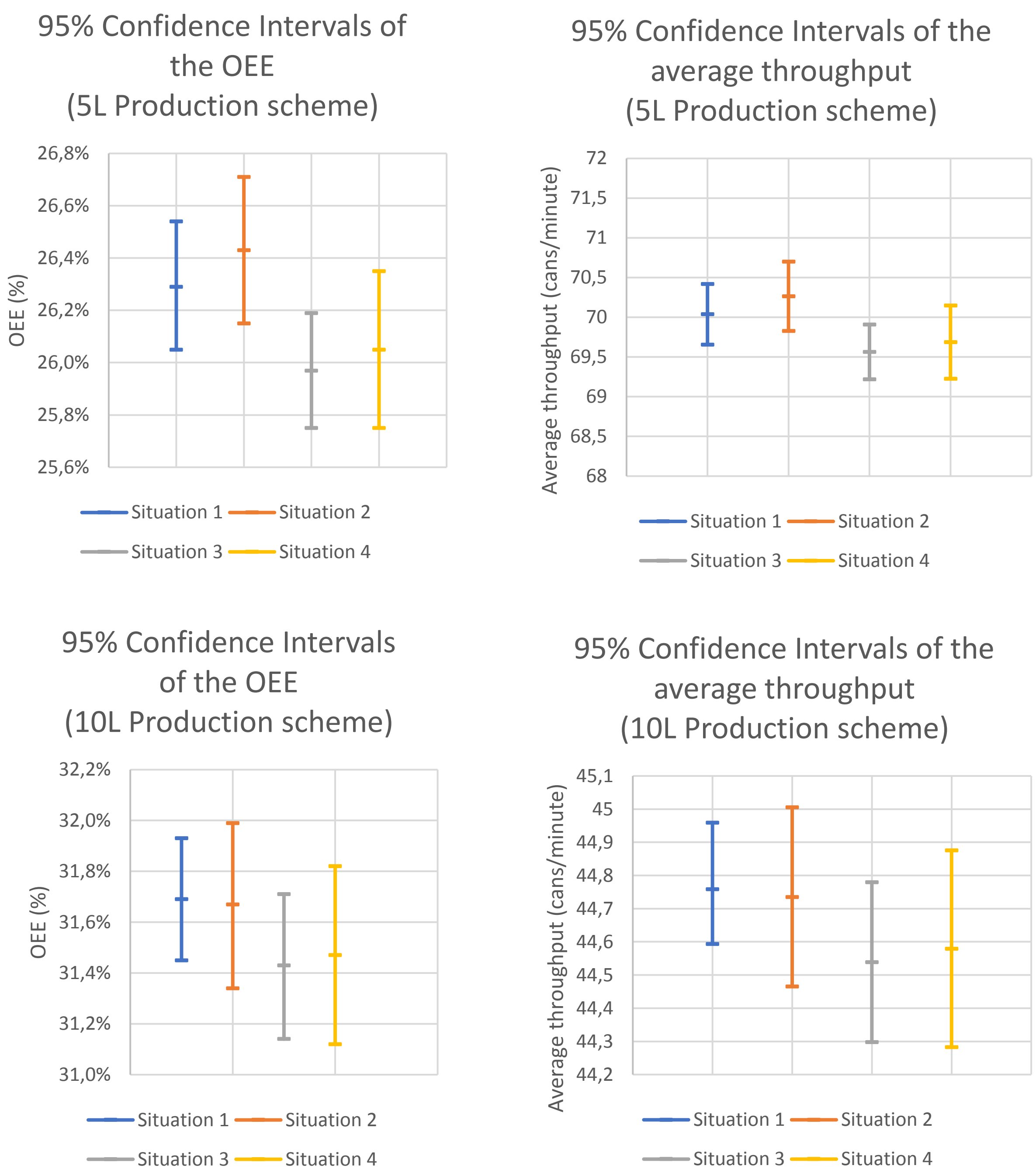

Figure A6.1 | 95% Confidence intervals for the OEE (%) and average throughput (cans/minute) of both production schemes

Appendix 7 Example calculation of the deterministic model

In this appendix, an example calculation of the deterministic model is shown, in this case for the product type 5L_Type1. This example calculation is presented below. Note that there are six workstations in this production line, thus n equals 6.

At first, the availability of the depalletizer, sleever, filler/capper, packing machine, tape machine and the box labeler are calculated. The availability of the depalletizer, for example, is calculated as follows:

$$A_1 = \frac{MTTF_1}{MTTF_1 + MTTR_1} = \frac{30}{30 + 1.5} \approx 95.24\%$$

After that, the availability of the production line can be calculated by taking the product of the availabilities of all the workstations, as it is a serial production line:

$$A_{PL} = \prod_{i=1}^{6} A_i = 95.24\% \times 83.33\% \times \ldots \times 90.91\% \approx 69.63\%$$

Now that the availability of the production line is calculated, the average throughput when the production line is in steady state can be calculated. As the processing speed of the bottleneck determines the throughput of the production line, the average throughput of the production line in steady state can be calculated by using the formula:

$$AvgTP = A_{PL} \times ProcSpeed_B = A_{PL} \times \min\{ProcSpeed_1, \ldots, ProcSpeed_6\} \approx 69.63\ cans/minute$$

Right now, the time till the steady state can be calculated, using the following formula:

$$TTST = \frac{D_6}{LineSpeed} + \sum_{i=1}^{5} CycleTime_i = \frac{89}{1} + 73.8 = 162.8\ seconds$$

Now that the time till the steady state and the average throughput in steady state are calculated, the total time that is needed to produce a batch can be calculated, using the following formula:

$$TBT = TTST + \frac{BatchSize}{\frac{AvgTP}{60}} = 162.8 + \frac{2000}{\frac{69.63}{60}} \approx 1886.2\ seconds$$

Now that the total time to produce a batch is calculated, the average throughput can be calculated, using the following formula:

$$AverageThroughput = \frac{BatchSize}{\frac{TBT}{60}} = \frac{2000}{\frac{1886.2}{60}} \approx 63.6\ cans/minute$$