Improving the Overall Equipment Effectiveness of a Cutting and Planing line by eliminating Short Stops

BSc thesis Industrial Engineering & Management by Gerco Mussche

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Improving the Overall Equipment Effectiveness of a Cutting and Planing line by eliminating Short Stops

A thesis submitted in partial fulfillment of the requirements for the degree of

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Preface

Dear reader,

In front of you lies the bachelor thesis "Improving the Overall Equipment Effectiveness of a Cutting and Planing line by eliminating short stops". This study has been performed at Phoenix Pallets B.V. as a final assignment for my bachelor Industrial Engineering & Management.

During the internship period, I have learned many skills and gained a lot of knowledge, and this learning experience would not have been possible without the aid and support of many people. First of all, I am profoundly grateful to Kristiaan Timmer, my supervisor at Phoenix Pallets B.V. His experience in supervising graduate students combined with his unstoppable enthusiasm for the art of process improvement was very helpful to me whenever I felt stuck in my research.

The other employees of Phoenix Pallets B.V. have also been very cooperative and helpful to me and were always available for my questions. A special thanks goes out to Maurits, Marcel and Klaas who went the extra mile for me and contributed a lot to this research with their practical knowledge.

Furthermore, I would like to express my gratitude to Marco Schutten for his supervision on behalf of the University of Twente. He provided me with all the help I needed even in these unpredictable and demanding times, and his knowledge of and experience with research methodology was very helpful to me. Next to that, I want to thank Wouter van Heeswijk for his willingness to be my second UT supervisor. Without the valuable and critical feedback of both Marco and Wouter, the report in front of you would be of a considerably lower level.

Last but not least, I want to thank my good friend Bram Zentveld for supporting me throughout the process of writing this thesis. Since he is going through the same situation right now, he understood exactly my doubts and struggles, which makes that our weekly meetings really helped me with writing this thesis.

I have enjoyed my stay at Phoenix Pallets B.V., and I am proud of the results of my project. I hope the company can create a lot of advantage out of my findings.

Enjoy reading!

Gerco Mussche

Staphorst, June 2021

Management summary

Phoenix Pallets BV made a lot of data available for this research that is not destined for the outside world. Therefore, quantitative values that are used in this thesis are multiplied by a factor X or by a factor Y due to the confidential nature of the data. For more information about this data anonymization, see Appendix 8.3.

Phoenix Pallets B.V. manufactures wooden pallets and provides packaging services. In order to be one step ahead of their competitors, they installed a new cutting and planing line in their sawing department. Ever since the installation of this line, Phoenix is busy improving the Overall Equipment Effectiveness (OEE) of this line, which was on average 53.9% in 2020. One of the issues they have not been able to tackle yet, is the high frequent occurrence of short stops. Short stops are machine stops between 20 and 45 seconds, and they occur quite often. In 2020, 4.6% of the total available time in this year was wasted with short stops, which equals on average 0.63 short stops per kilometer. In order to reduce this figure, we answer the following research question:

"How can we decrease the occurrence of short stops on the Cutting and Planing line of Phoenix to at most 2% of the total available time?"

In this research, we use a combination of Lean Manufacturing and the Theory of Constraints. Identifying the constraint that is the root cause of most short stops is the first step of the Five Focusing Steps from the Theory of Constraints and during this step, we apply various principles of Lean Manufacturing, like Gemba walks to get a better understanding of the problem itself and the current situation, an Ishikawa diagram that proposes possible causes for short stops, and the Why-Why Analysis to find the underlying reasons for the existence of the root causes. Next, we execute steps 2, 3 & 4 of the Five Focusing Steps from the Theory of Constraints to find the best improvement strategy that eliminates short stops.

When searching for root causes of short stops, we first investigate which factors influence the occurrence of short stops, and then what the underlying root causes for these factors are. It turns out that the two biggest influences on the number of short stops are the crew that is working, and the length of the boards the cutting and planing line processes. The difference between the two crews is caused by a difference in work method, and the used method depends currently on the insight of the operators because there are no Standard Operating Procedures (SOPs) documented. Next, the differences between the board lengths exists because when processing short boards, the infeed is idling more often. If the infeed is idling, it means that the second separator (the activity where all boards separated in order to check their individual quality) does not deliver enough boards to keep the planing machine busy. There are a few reasons why the second separator cannot keep up with the speed of the planing machine:

- The buffer in front of this separator is often not large enough, which results in an empty cycle.
- The top speed of the separator is only 72 cycles/min while the manufacturer promised that it would be 80 cycles/min.
- Even if the top speed was 80 cycles/min, some combinations of board length and planing speed still would not be possible for the separator.

In order to solve these problems, the company should first exploit the second separator, which means making the most of what is available. To do this, they should upgrade the software of the separator by programming a new speed level and importing this into the current program of the separator, and they should increase the buffer in front of the single feed unit by adapting the location of a sensor. Next, it is important to subordinate everything else, which involves selecting a higher speed level for the first separator, so it can always keep up with the speed of the second separator. To avoid an empty buffer after the de-stacker (the activity at the beginning of the line where packages of wood are de-stacked) while the de-stacker is picking up a new package of wood, the operators should release manually the last layers of each package of wood when processing short boards, to make sure that there is always enough wood to process while the de-stacker is changing packages. This is part of the recommendation to develop and implement new SOPs, because in the current situation there are no SOPs documented. Within Lean Manufacturing, this type of waste is called 'Mura': A lack of consistency in a production process because activities are not properly documented, with the result that different people at different times perform a task differently, which means that the output of the production process is not surprisingly different as well.

In these first two steps of the improvement strategy (Exploit & Subordinate), no costs are involved. The cutting and planing line was installed only two years ago, so it is still under warranty and therefore updating the separator speed to the speed it should be costs nothing. Furthermore, replacing a sensor and training the operators to apply the new work methods may cost some time, but there are no direct costs involved. Only when these two steps do not achieve the desired result, the improvement strategy is expanded with step 4 of the Five Focusing Steps (Elevate). Here, some more drastic changes to the cutting and planing line eliminate the second separator from being the constraint, which requires a major investment. We explain two possibilities in this report: implementing a system with two separate two chain conveyors that work independently of one another, and removing the second separator entirely. The exact amount for these drastic changes is still unknown, which is why we advise the company in our recommendations to investigate the costs involved in the Elevate step.

After implementing all stages of the improvement strategy, all boards will behave like the longest boards which means that on average, the number of short stops per kilometer will be on average 0.45. This means that the number of short stops decreases by 29%. In reality, 4.6% of the available time is lost to short stops, and if this figure decreases by 29%, only 3.3% of the available time is lost to short stops. At the start, 2% was chosen as the norm so that this research had a figure to work towards. Unfortunately, this norm cannot be achieved with the proposed improvement strategy. However, due to the nature of the short stops we eliminate, we enable the planing machine to reach for all board lengths the average speed of the longest board lengths, which is approximately 188 m/min. Since the maximum speed of the planing machine is 200 m/min, achieving 188 m/min on average makes the Performance component of the OEE 188/200 = 94%. If we take this into account, the OEE after implementing the improvement strategy will become 63.2%, based on the average OEE of 2020. The OEE would only have been 56.0% if we met the norm of 2% without being able to increase the planing speed. Therefore, we can say that due to this side effect, this project can still be considered as a success.

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Introduction

This chapter is the general introduction to this research, which we conduct at Phoenix Pallets BV. Section 1.1 gives an introduction to Phoenix Pallets BV to get a better idea of the host organization of this research. Section 1.2 describes what challenges this company faces nowadays, and Section 1.3 identifies the core problem for this research in the context of these challenges. Next, Section 1.4 contains the research design, which provides the structure for the rest of this report, and Section 1.5 mentions the plan of approach that is used to answer the research questions. This chapter finishes with mentioning the deliverables that this research yields and how the rest of this thesis is structured, in Section 1.6 and Section 1.7 respectively.

1.1 Company information

This research takes place at Phoenix Pallets BV in Hasselt, which is a company that was already established in 1891. They started with the production of wooden barrels for butter, but gradually they made the switch to producing pallets and they conquered new markets. Nowadays, Phoenix is an internationally operating supplier of wooden pallets and packaging activities. The company keeps the whole process in-house, from design to production to delivery. In this way, they can always maintain the quality, ensure low costs and stay flexible.

Phoenix' strategy focuses on two objectives (Foresco Group, n.d.):

1. Sustainability and the environment: A sustainable production process is a requirement for Phoenix. That is why they only use wood from sustainable sources for their pallets, and they are fully certified for all aspects of environmentally friendly production. Next to that, pallet pooling is also one of their core activities. This means that customers can come to Phoenix with old pallets. The repair and re-use of pallets fits perfectly in their sustainability mindset.
2. Flexibility and just-in-time delivery: Phoenix delivers wooden pallets in all the usual sizes, and they make pallets that comply with the customers' particular needs. Phoenix is also a specialist in just-in-time deliveries. With their computer-controlled machines, they produce pallets at speed in any required size and number. Ordered pallets are delivered within 24 hours, even if they are not in stock.

In 2020, Phoenix was acquired by the Foresco Group, a Belgian manufacturer of custom-made pallets and wooden packaging and market leader in the business. The Foresco Group has over 500 employees divided over 11 establishments in Belgium and the Netherlands, and although these 11 establishments have different brand names, the underlying operations are integrated in such a way that production always takes place at the best-qualified site, while there is also an back-up option in case an incident occurs. The production sites in Hasselt and Assen operate under the name of Phoenix, and in this research we investigate a specific problem at the plant in Hasselt.

1.2 Context description

This section analyzes the challenges that manufacturing organizations, including Phoenix, have to deal with. Nowadays, manufacturers are under a lot of pressure to improve customer satisfaction and minimize production costs (Raouf, 1994). According to Miyake (1999), organizations cannot operate the same way at all times, but they should respond dynamically to changes in the markets. This requires the establishment of long-term strategies that improve the competitiveness of the organization, which means that organizations should constantly be monitoring their environment and promoting internal improvements. Hayes and Pisano (1994) think that manufacturing organizations that implement various improvement programs in order to develop unique operating capabilities can be one step ahead of their competitors. In order to obtain this competitive advantage, organizations should be aware of a few things. First, they should understand that the primary way manufacturing adds value to the organization is by enabling it to do certain things better than its competitors can. What these things are and how they can be done better is different for individual organizations. Second, an organization should develop a plan on how to acquire the capabilities it wants to have. This is where they should think about which manufacturing improvement approaches they are going to use. Section 1.3 describes what these challenges mean for Phoenix, and how this research can contribute to the competitiveness of Phoenix.

1.3 Core problem identification

As mentioned in Section 1.2, enhancing the competitiveness is one of the largest challenges for manufacturing companies, and this is the case for Phoenix as well. In order to be able to do certain things better than their competitors and hence be one step ahead of them, Phoenix installed a new cutting and planing line in their sawing department: the Ledinek/Kallfass line. Ledinek refers to the planing components of the line, while Kallfass includes everything else: the supply of raw material, the cutting part and the part that stacks the finished products. Chapter 2 describes in more detail the different components that belong to both parts of the line. Since the installation of the cutting and planing line two years ago, the management team of Phoenix has been busy improving its Overall Equipment Effectiveness (OEE) and they have already made significant progress. Before we discuss the issues that they have not been able to tackle yet, an explanation of what the OEE entails follows first.

Overall Equipment Effectiveness

According to Slack, Brandon-Jones & Johnston (2016), the theoretical capacity of a process, in this case the wood planing process, is rarely achieved in practice. Not all of the incurred losses are necessarily avoidable. Some of these losses are even to some extent predictable, for example, different products have different requirements, so the machine has delays when switching between tasks. However, reduction in capacity can be the result of less predictable events as well. For example, quality problems, labor shortages, a breakdown of the machine or delays in the supply of raw materials can all reduce capacity. This reduction in capacity is referred to as ‘capacity leakage’, and a popular method of assessing this leakage is the Overall Equipment Effectiveness, invented by Nakajima (1988). The OEE is calculated as follows:

$$OEE = Availability * Performance * Quality * 100\%$$

Figure 1 shows how the three components of the OEE are calculated. The OEE works on the assumption that some capacity leakage reduces the availability of a process. For example, availability can be lost through time losses such as changeover losses and breakdown failures. Some capacity is lost through performance losses, such as when equipment is idling and when equipment is running below its optimum work rate. Finally, not everything processed by a machine will be error-free. So, some capacity is lost through quality losses (Slack, Brandon-Jones & Johnston, 2016).

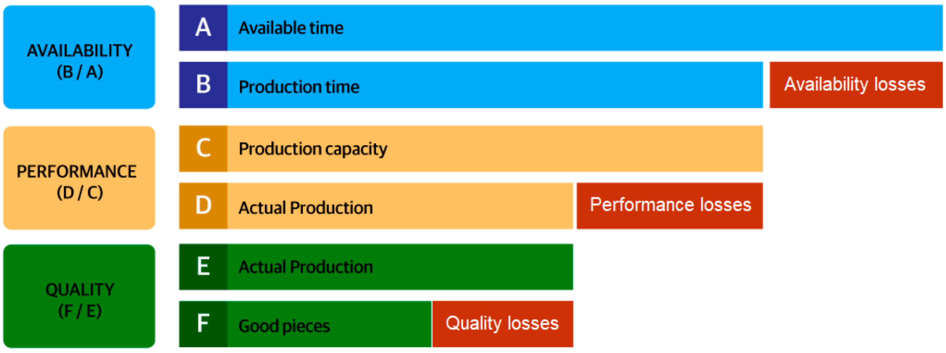


Figure 1: OEE calculation

The Six Big Losses

Before the start of the project, the OEE of the cutting and planing line is on average between 50% and 60%. There are many possible reasons why the OEE is lower than desired. Nakajima (1988) categorized all these reasons in six groups: The Six Big Losses (Table 1). According to the Six Big Losses, short stops are Performance losses because it is challenging to register manually all short stops due to their high frequent occurrence and short duration, so it is easier to consider the sum of all short stops as a reduction in speed (Koch, 2007). However, the cutting and planing line that is the subject of this research is equipped with sensors that keep track of all the individual short stops and gather them as a separate time category in the Availability losses. Therefore, we consider short stops as Availability losses in this research as well.

Overall Equipment Effectiveness	Six Big Losses
Availability losses	Equipment Failure
	Setup and Adjustments
Performance losses	Idling and Short Stops
	Reduced Speed
Quality losses	Process Defects
	Reduced Yield

Table 1: The Six Big Losses (Six Big Losses, n.d.)

Core problem identification

Since the OEE takes into account many different aspects of an production line, there are also many approaches to improving the OEE of a production line. So, in order to narrow down the scope of this research, we focus specifically on one loss. Before determining which loss is going to be the core problem of the research, we investigate where we can make the most impact. Figure 2 shows the average OEE of March 2021, the month prior to the research.

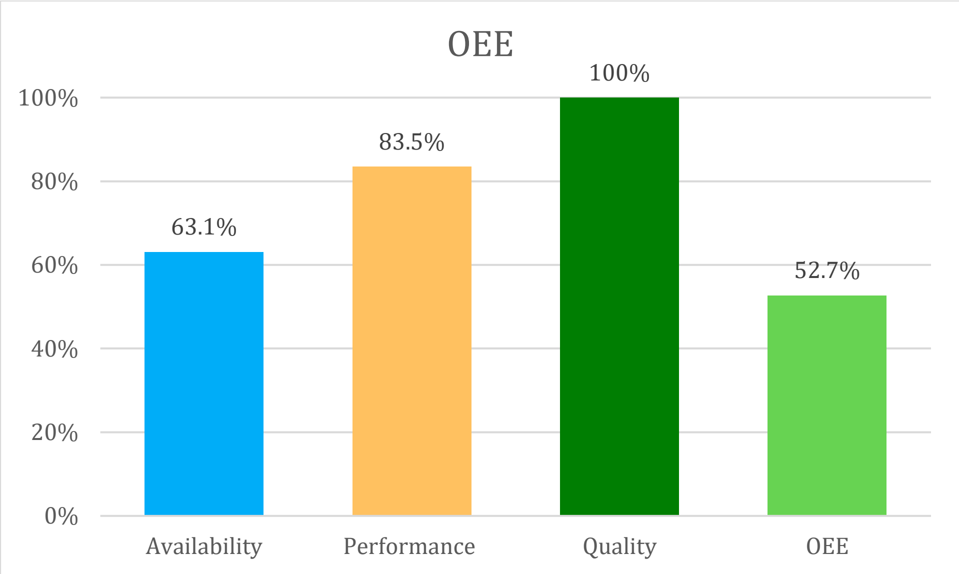


Figure 2: Average OEE in March 2021

The Quality component of the cutting and planing line is by definition always 100%, because wrong boards are removed from the line in an early stage and used for other purposes, so they are not registered as wrong output. Even if something goes wrong with cutting the boards for example, and the final output contains some defect boards, these boards can still be used for other purposes, so they are not considered as waste. However, despite the fact that the quality of the final output is by definition 100%, it does not mean that there is no waste in any of the stages of the cutting and planing line at all. Section 5.3.2 elaborates on the waste is caused at the cutting stage of the line, and how the company keeps track of it.

Next, the machine ran in March 2021 on average 16.5% below its maximum speed, hence the Performance losses. The operator can increase the production speed himself. However, it turns out that an increased production speed causes more short stops. Section 4.3.2 explains in more detail why this is the case, but the fact that it happens suggests that the occurrence of short stops should be solved first before the production speed, and hence the Performance component, can be increased.

Short stops are part of the Availability component of the OEE. Figure 3 shows the biggest losses that are responsible for the low availability. In this graph, only losses that cost more than 1% of the available time are included. There are also many losses that cost 1% of the available time or less; these losses are gathered in the category 'other'. The top three losses in Figure 3 are:

1. Changeovers: the process of converting the line from running one product to another;
2. Short stops: the planing machine is idling between 20 and 45 seconds;
3. Planing tool changes: replacing the planing tool when it is worn-out.

According to the management team of Phoenix, it is hard to reduce the changeover times and tool change times further since it is already optimized using SMED (Single-Minute Exchange of Die). However, with regard to the short stops, they have not had the time to look into possible causes for these short stops in depth yet, let alone solve these problems. This makes that, combined with the aforementioned fact that the short stops limit the production speed, we choose in consultation with Phoenix the high frequent occurrence of short stops as the core problem for this research.

Figure 3: Biggest availability losses in March 2021

Short stops

A short stop is idle time that does not take a lot of time, but these stops occur quite often (Teeuwen & Kersten, 2013). Short stops on the cutting and planing line happen when the planing machine is idling between 20 and 45 seconds. In case this lasts longer than 45 seconds, the operator assigns a failure code to the stop and it is identified as a certain availability loss. If the planing machine is idling for shorter than 20 seconds, the lost time is neither considered as a short stop nor as another availability loss, but as a reduction in speed instead, which means that they are the original short stops as described by Koch (2007), which we mentioned before. This research focuses mainly on the short stops that take between 20 and 45 seconds, but in Section 5.3.2 we briefly analyze the stops under 20 seconds as well. A short stop occurs for example when multiple boards slide on top of each other and the operator does not notice it fast enough, so he has to stop the machine in order to rearrange the wood. These problems are solved easily, but the time loss in the long term is significant because it occurs often. To illustrate this, 3.7% of the available time was lost to 939 short stops in March 2021, which corresponds to more than 8 hours of lost time in only 1 month. Despite the fact that it is mostly known what happens during a short stop, the root causes why it keeps occurring is unknown to the management team of Phoenix.

Research objective

This research is meant to give insight into the root causes of short stops, and to come up with a strategy to reduce the number of short stops. Koch (2007) indicates that losses can only have one norm: 0. However, it is practically impossible to eliminate every short stop within the short time frame that is available for this project. This project is part of a strategy the company has to increase the OEE of the cutting and planing line by 10% within one year. We agreed that if this research can contribute to that goal with a few percent by eliminating short stops, it can be considered as a success. In 2020, the average time lost to short stops was 4.6% of the total available time, and the goal of this research is bringing that figure back to at most 2%. Despite the fact that this norm is determined intuitively and is consequently not very strict, it still gives us a figure to work towards and hence the action problem for this research is formulated as follows:

"The sum of all short stops as a percentage of the available time is on average 4.6%, and we want to bring this figure back to at most 2%."

1.4 Research Design

In order to solve the action problem mentioned in Section 1.3, we define the main research question as follows:

"How can we decrease the occurrence of short stops on the Cutting and Planing line of Phoenix to at most 2% of the total available time?"

Answering the research questions below gives ultimately the answer to the main research question. Each research question consists of several underlying knowledge questions, to which the answer gives us the required knowledge for answering the research questions.

RQ1: What is the current situation of the cutting and planing line?

a. How does the cutting and planing process work?
b. What is the current performance of the cutting and planing line with regard to short stops?

RQ2: What literature is useful for eliminating short stops?

a. Which techniques exist to identify the root causes of short stops?
b. What is the best approach to eliminate short stops?

RQ3: What causes the short stops?

a. Which factors influence the occurrence of short stops?
b. What are the underlying causes for these factors?

RQ4: What is the best improvement strategy for Phoenix?

a. How can Phoenix solve the previously found root causes, and hence eliminate most of the short stops?
b. Which costs and benefits are involved in this strategy?

1.5 Plan of Approach

To answer the in Section 1.4 mentioned research questions, we construct in this section a plan of approach that functions as the main structure for this research. This approach consists of multiple steps, which we explain below. These steps are globally in the order we execute them, but there does exist a continuous cycle between steps 2-4 because collecting and analyzing different types of data is relevant at many moments. Steps 1-4 each answer one of the research questions that are mentioned in the previous section.

1. Understanding the process

The first step focuses on defining the research problem and motivating the value of solving that problem. To do so, obtaining a thorough understanding of how the process in the sawing department works is very important, which is done by observing the process from raw material to finished product and talking to the employees on the work floor.

2. Composing a theoretical framework

In the next step, we analyze available literature and select it if it is useful for identifying and eliminating short stops.

3. Data analysis

This step first generates hypotheses that suggest possible root causes for the occurrence of short stops based on the experience of employees (step 1) and theory from the literature (step 2). Next, we review the data system of Phoenix to look for what is in there and what might be useful. Any missing data is collected through observation and/or interviews.

4. Solution generation

Now the root causes of the short stops are clear, we create in this step an improvement strategy for the cutting and planing line, including a cost-benefit analysis.

5. Constructing advice

The last step of the problem approach is to write an advisory report for the management team of Phoenix. This advice should have concrete recommendations on how the OEE of the cutting and planing line can be improved by eliminating short stops.

1.6 Deliverables

The deliverable that follows from this research is an advisory report for Phoenix. In this report, we intend to include the following things:

- Giving insight in the root causes for the short stops;
- Developing a strategy on how the company can eliminate most of the short stops;
- Calculating the costs and benefits that are involved in this strategy.

1.7 Report Structure

Chapter 2 explains how the cutting and planing process works, and what the current performance of this production line is with regard to short stops, which indicates the impact of the problem on the process. Next, Chapter 3 reviews the available literature in order to form a theoretical framework, which can be used to solve the problem. This theoretical framework is then used in Chapter 4, where we search for the root causes of short stops, and in Chapter 5, where we come up with a strategy to solve these root causes and hence eliminate most of the short stops. This report ends with Chapter 6, where we write our conclusions, recommendations for the company, and suggestions for further research.

2

Context analysis

This chapter aims to answer the following research question:

"What is the current situation of the cutting and planing line?"

To achieve this goal, this chapter consists of two sections that answer their own sub-question. Section 2.1 describes how the cutting and planing process works, and Section 2.2 discusses the current performance of this process. Combined, these sections give a good overview of the cutting and planing line's current situation.

2.1 Process description

This section answers the following sub-question:

"How does the cutting and planing process work?"

A production line consists of many separate components that work together in order to create the desired end product. To get the answer to the sub-question of this section, we describe below all these components, and we show in a flow chart (Figure 10) how these components work together.

Components

1. Tilting de-stacker

The process starts with a package of a few hundred wooden boards that is put on a conveyor belt by a forklift. The conveyor belt transports this package to the de-stacker, where the package is de-stacked so that each individual board can be planed and cut. De-stacking works as follows: the package is pivoted by approximately 45 degrees (Figure 4). Next, the package is lifted and layer by layer, the boards fall over the edge (Figure 5).

2. Separator 1

The line contains two separators. The function of the first one is to form a material film/carpet, which ensures that no boards lie on top of each other anymore (Figure 6). There should always be a buffer between the de-stacker and the first separator. In case this buffer gets empty, the de-stacker is lifted a little bit more and the next layer of boards falls over the edge. This way, the separator has always boards to pick up, and there are always boards at the quality-checking station as well.

Figure 4: Pivoting the package

Figure 5: Tilting the package

Figure 6: Forming a material film

3. Quality-checking station

The quality-checking station is occupied by an operator. Here, the operator assesses each board. He marks the boards that should be turned around by placing the end of the board just outside the conveyor system, and the boards that are broken by pulling that board even further out.

4. Single feed unit

After short time intervals, the single feed unit (Figure 7Figure 6) releases a board. To release a board, there should be a buffer in front of the single feed unit of a certain length, based on the width of the boards. This is necessary, because having a buffer of a few boards before the first one can be released ensures that the first one lies still at the moment of release.

5. Separator 2

The first separator made a single layer of the boards, but the second separator goes one step further and separates every single board (Figure 8). This separator is basically a chain conveyor with pockets on it, and since the single feed unit released every board individually (step 4), each pocket on this separator is now filled with at most one board. This way, the next two steps in the process can be performed. The single feed unit and the second separator need to run at the same speed. If that is not the case, there could be either empty pockets on the separator, or two boards in one pocket. Empty pockets are just a waste of space, while two boards in one pocket make it impossible for both the turning- and the sorting system to function properly.

6. Turning system

If the operator at the quality-checking station marked a board as upside down, a sensor on the turning system notices it if that board is pulled out a bit, and activates the turning system.

7. Sorting system

In case a board is marked as broken at the quality-checking station, the sensor of the sorting system notices that the end of this board is over the edge of the conveyor belt, which activates the sorting system and that board is disposed from the line.

Figure 7: The single feed unit

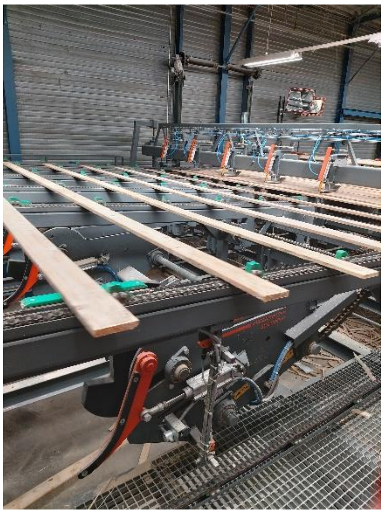


Figure 8: Separator 2

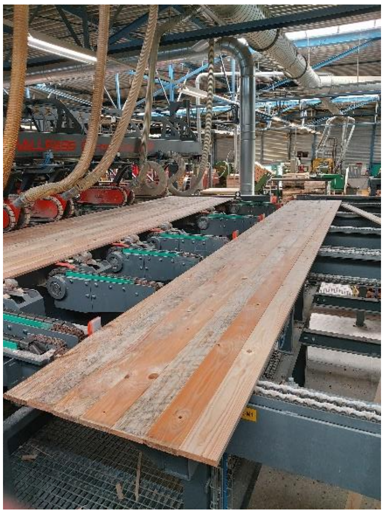


Figure 9: Cutting happens per layer

8. Infeed

The infeed feeds the boards to the planing machine at a speed of max. 12 km/h. Until the infeed, the boards are transported in transverse direction, but the boards are planed in longitudinal direction. Therefore, the infeed accelerates the boards in longitudinal direction.

9. Planing machine

The planing machine planes all four sides of a board at high speed.

10. Slow-down belt

Since boards leave the planing machine at a speed of max. 12 km/h, a slowdown belt is installed to bring the speed of the boards back to 0. The reason why the speed should become 0 is because the boards are planed in longitudinal direction, and after the planing machine, the boards are again transported in transverse direction.

11. Layer separator

At the layer separator, the amount of boards is collected that form together exactly one layer on a package of wood (Figure 9). Once there are enough boards, this layer is released and the next boards form a new layer.

12. Multiple cross-cut saw

The layer of boards that is formed at the previous step is cut to the desired length by the multiple cross-cut saw.

13. Stacker

After the boards are cut, they move to the stacker which puts layers that are ready on top of a new package of wood, and wooden sticks are put between a certain amount of layers. These wooden sticks increase the stability of the package, and ensure adequate air circulation during drying in order to accelerate the drying process. This drying process is not a part of the cutting and planing line, and is therefore not relevant for this research.

14. Strapper

This machine puts some straps around the packages for additional stability. Lastly, a forklift takes the package of wood away and brings it to another department of the plant, where pallets are made.

Process flow

Figure 10 shows the flow chart for the cutting and planing line. This flow chart is divided into three parts: the Kallfass components, the Ledinek components, and the strapper which is manufactured by Fromm. Together, the components from these three brands form the cutting and planing line.

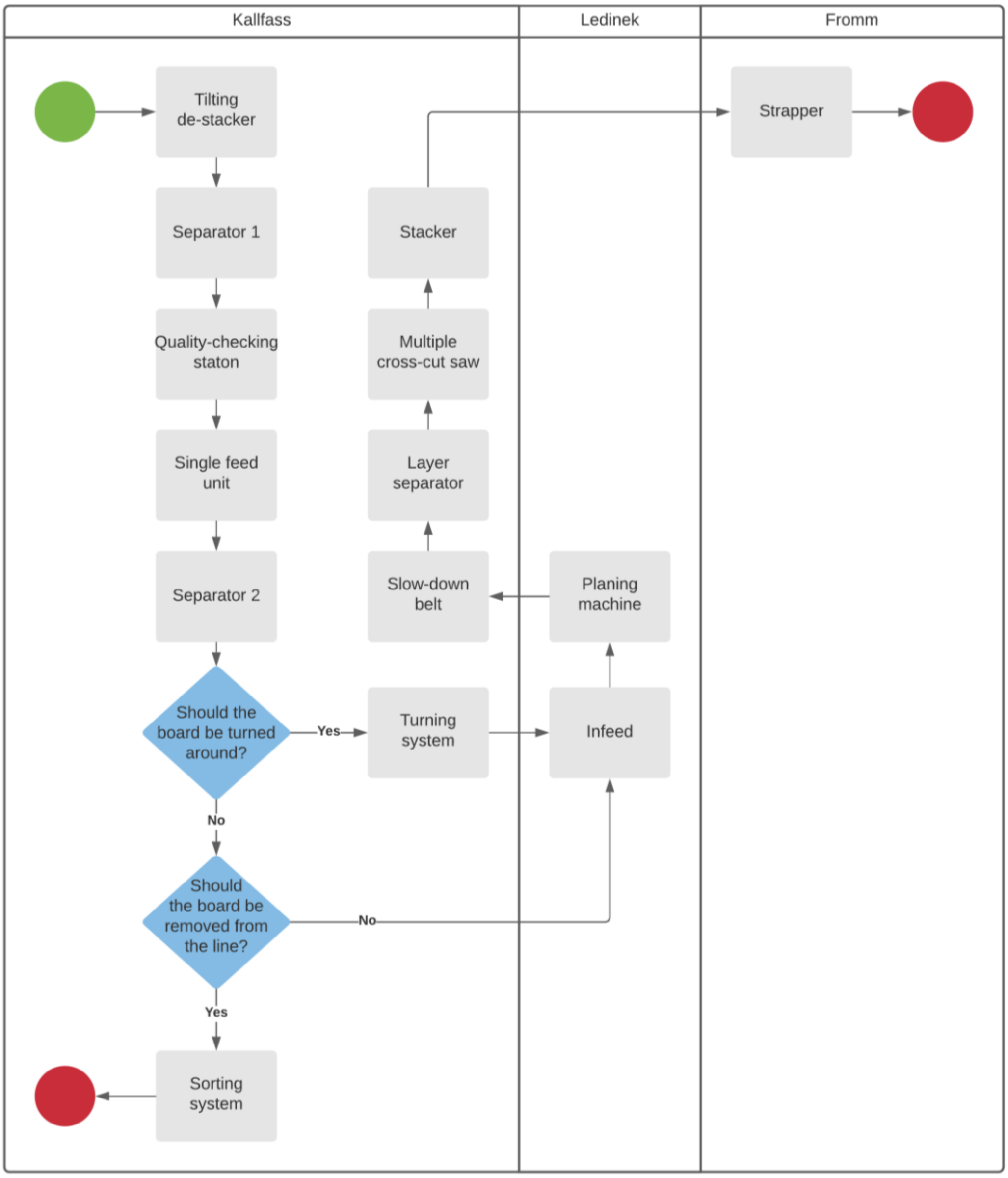


Figure 10: Process map for the cutting and planing line

2.2 Current performance

Chapter 1 gave already a brief introduction to the performance of this line, and this section elaborates on this by answering the knowledge question:

"What is the current performance of the cutting and planing line with regard to short stops?"

Chapter 1 already mentioned something about the occurrence of short stops in March 2021. Here, we look at the occurrence of short stops in more detail, based on all of 2020. In 2020, the total available time was 3,382 hours. From this available time, 4.6% was wasted with short stops, which equals 154 hours. In the rest of this thesis, we express the occurrence of short stops as the number of short stops per kilometer output. To calculate this dependent variable, we use different data sources. First, Phoenix has production logs available that show for every day which batch of wood has been processed, when the processing of that batch started and finished, and how much output that batch yielded. For example, Table 2 shows the production log for the first working day of 2021. In Table 2, the output of each batch is multiplied by a factor X because the original values are considered to be confidential by the company. In the rest of this thesis, columns of tables, figures and in-text values that are multiplied with this factor X are indicated with an asterisk (*), in order to make a distinction between anonymized and non-anonymized values.

Batch identification number	Start time	Stop time	* Output (m)
1	6:00 AM	9:00 AM	32,968
7	9:00 AM	9:40 AM	1,464
9	9:40 AM	10:25 AM	10,321
10	10:25 AM	11:30 AM	12,552
12	11:30 AM	12:00 PM	5,775
13	12:00 PM	12:55 PM	4,671
14	12:55 PM	3:07 PM	20,419
15	3:07 PM	3:46 PM	5,849
16	3:46 PM	4:00 PM	2,481
25	4:00 PM	11:24 PM	51,047

Table 2: Production log for January 4, 2021

Next to that, we can download for each shift a Gantt chart with the OEE activities of that shift, including timestamps. Figure 11 shows the Gantt chart for the first working day of 2021, and Table 17 in Appendix 8.1 contains the corresponding timestamps. Combining the production logs and Gantt charts enables us to calculate for each batch the number of short stops that occurred per kilometer output. Table 3 shows what this looks like for January 4, 2021.

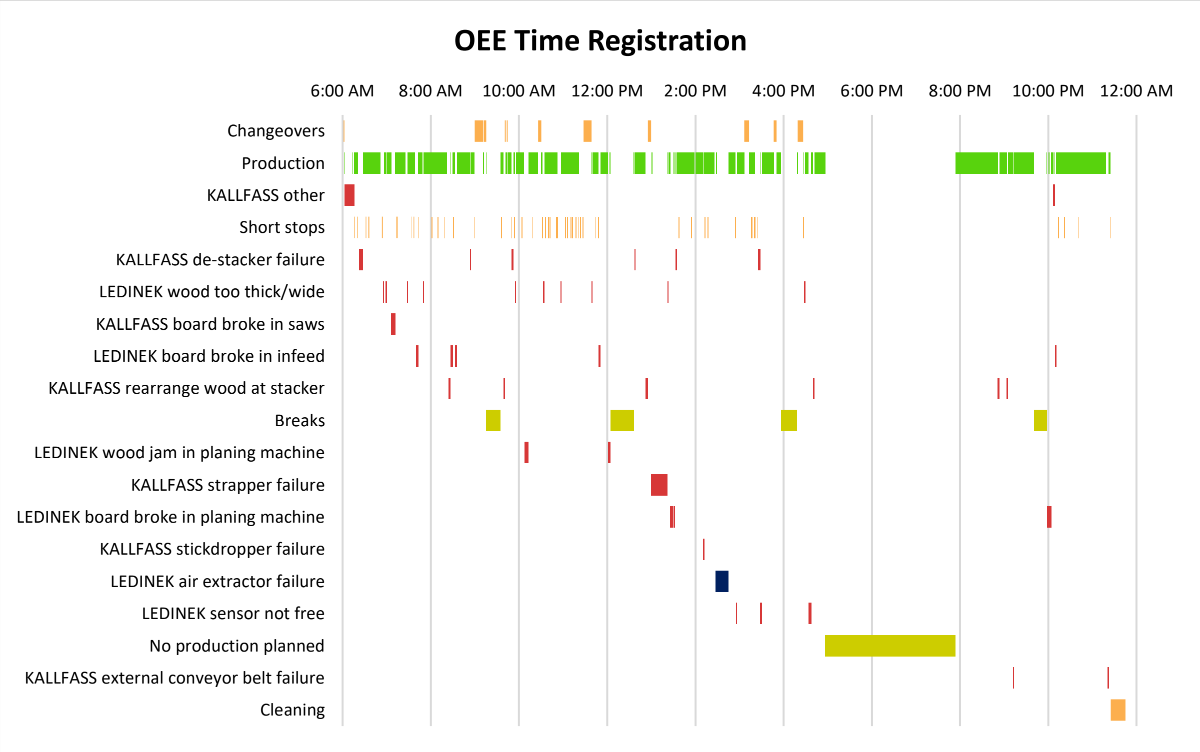


Figure 11: Gantt chart for January 4, 2021

Batch identification number	* Output (m)	* Short stops	Ss/km
1	32,968	32	0.97
7	1,464	2	1.21
9	10,321	7	0.69
10	12,552	28	2.26
12	5,775	4	0.61
13	4,671	0	0
14	20,419	9	0.43
15	5,849	9	1.52
16	2,481	0	0
25	51,047	9	0.17

Table 3: Short stop occurrence on January 4, 2021

Doing these calculations for all shifts since the beginning of 2020 enables us to show the current performance of the cutting and planing line with regard to short stops. Figure 12 shows the weekly occurrence of short stops since the beginning of 2020. What we notice immediately when looking at this graph, is the high peak between weeks 4 and 9 of 2021. In Chapter 4, we investigate why this peak exists. Next to that, the number of short stops varies between 0.4 and 0.8 short stops per kilometer output, without any large peaks or lows besides the aforementioned peak in the beginning of 2021. If we do not take that peak into account, we see that the number of short stops stays on average constant over the course of 16 months, with an approximate value of 0.63. This means that none of the measures the company has taken in that time really had an influence on the frequency of short stops. With that in mind, it is not surprising that the company hired someone who could approach the problem with fresh ideas.

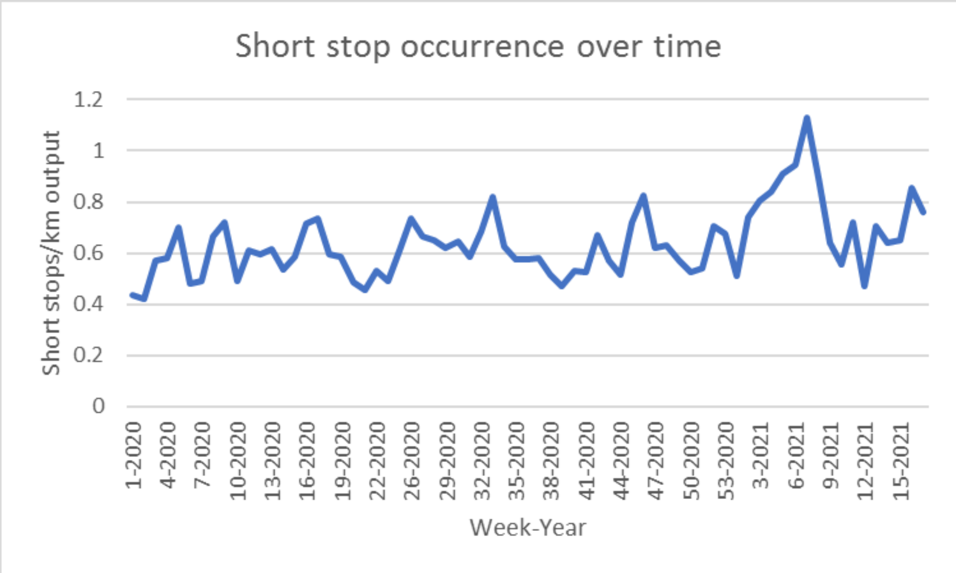


Figure 12: Short stops occurrence 2020-2021

2.3 Chapter conclusion

This section concludes this chapter by giving a brief summary, which answers the research questions of this chapter. The main research question was:

"What is the current situation of the cutting and planing line?"

We answer this question by answering the two sub-questions below.

a. How does the cutting and planing process work?

Figure 10 shows how the cutting and planing line works, and this figure shows that the line consists of many different components. All these components should work synchronized together in order to create a smooth material flow. This means that for a line with many different components it can be harder to maintain a good material flow, especially if these components are closely behind each other, but that is something we discuss further in Chapter 5.

b. What is the current performance of the line with regard to short stops?

As mentioned above, the number of short stops varies approximately between 0.4 and 0.8 short stops per kilometer output, with an average of 0.63. Next to that, we noticed that a high peak in the number of short stops in February 2021, but we do not know yet what caused this peak. In Chapter 4, we investigate why this peak exists.

3

Literature review

In this chapter, we introduce the theory that can be of help with identifying the root causes of short stops, as well as methods to eliminate these short stops. This chapter answers the following research question:

"What literature is useful for eliminating short stops?"

To answer this question, we start in Section 3.1 with an explanation of the concept Lean Manufacturing, and different Lean tools that can possibly be useful for this research. Next, we explain the Theory of Constraints in Section 3.2. The reason why we choose these two particular theories is because they are both well-known production improvement methods that offer a huge variety of useful tools. Section 3.3 discusses the differences between Lean Manufacturing and the Theory of Constraints. This chapter finishes with Section 3.4 where we summarize our findings and answer the research questions.

3.1 Lean Manufacturing

The basis of Lean Manufacturing is the Japanese car manufacturer Toyota. Eiji Toyoda and Taiichi Ohno initiated the concept of the Toyota Production System (TPS), or what is now known as Lean Manufacturing (Dhiravidamani, Ramkumar, Ponnambalam & Subramanian, 2018). A formal definition for Lean Manufacturing is: *"A management approach to manufacturing that strives to make organizations more competitive in the market by increasing efficiency and decreasing costs through the elimination of non-value-added steps and inefficiencies in the process"* (Belekoukiasa, Garza-Reyes & Kumarc, 2014). For many people, the phrase 'Lean Manufacturing' is synonymous with removing waste – and eliminating waste is certainly a key element of any Lean practice. The ultimate goal of practicing Lean Manufacturing however, is not simply to eliminate waste, but also to sustainably deliver value to the customer. To achieve that goal, Lean Manufacturing defines waste as anything that does not add value to the customer. This can be a process, activity, product, or service; anything that requires an investment of time, money or talent but does not create value for the customer is waste. Idle time, underutilized talent, excess inventory, and inefficient processes are all considered waste by the Lean definition. Lean Manufacturing provides a systematic method for minimizing waste within a manufacturing system, while staying within certain margins of control such as productivity and quality (Lynn, n.d.). This method consists of several techniques and principles and together they constitute a toolbox that helps eliminating waste in every area of production. Below, we briefly discuss a selection of some important techniques and principles within Lean Manufacturing. The techniques and principles in this selection cover all a different area of Lean Manufacturing, in order to avoid that this theoretical framework pushes the research already in a certain direction, which may cause a tunnel vision.

Cause-and-effect diagram

A cause-and-effect diagram is considered to be a particularly effective method of helping to search for the root causes of an industrial problem. They can be used to identify areas where further data is needed (Slack, Brandon-Jones & Johnston, 2016). A traditional cause-and-effect diagram is the Ishikawa diagram, invented by the Japanese professor Kaoru Ishikawa in the 1960s (Botezatu, Condrea, Oriana, Hriţuc, Eţcu & Slătineanu, 2019). It is also known as a fishbone diagram because of its shape (Figure 13). In this diagram, the 'fish head' represents the main problem. The potential causes of the problem, usually derived from brainstorming sessions or research, are indicated in the 'fish bones' of the diagram (Heerkens & Van Winden, 2017). For these fishbones, the old-fashioned subdivision is often used: man, machine, material, method, milieu and measurement. The creator of the diagram is, however, free to choose whatever heading for a cause subdivision he wants (Slack, Brandon-Jones & Johnston, 2016).

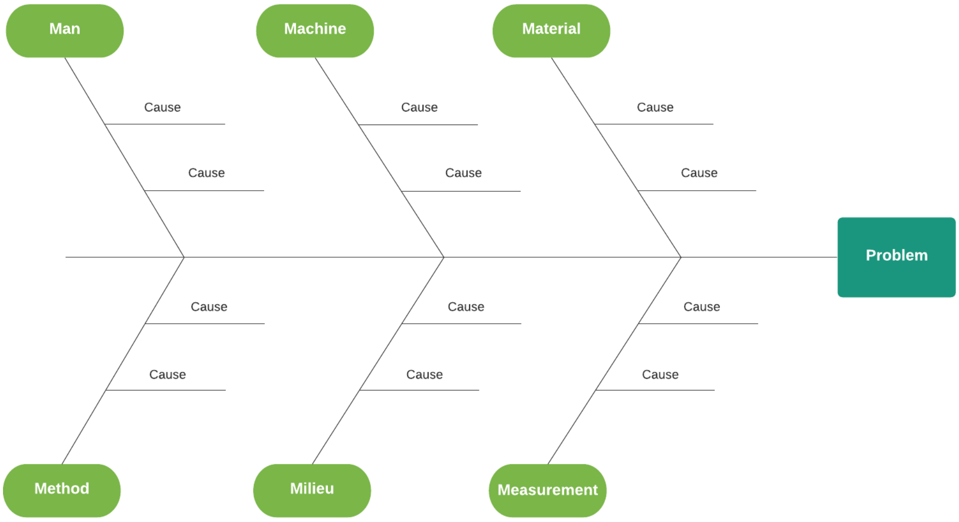


Figure 13: Ishikawa diagram

Muda, mura, muri

As often in Lean Manufacturing, Japanese terms are used to describe core principles, and waste elimination is absolutely a core Lean idea. The terms muda, mura and muri are Japanese words conveying three causes of waste that should be reduced or eliminated (Slack, Brandon-Jones & Johnston, 2016):

- Muda: Activities in a process that do not add value to the operation or the customer. The main causes of these wasteful activities are poorly communicated objectives, or an inefficient use of resources.
- Mura: Lack of consistency that results in periodic overloading of staff or equipment. For example, if activities are not properly documented, different people at different times perform a task differently, and the result of this is not surprisingly different as well.
- Muri: The idea that unnecessary or unreasonable requirements put on a process will result in poor outcomes. This can be avoided by means of effective planning combined with appropriate skills.

These three causes of waste are related: if a process is inconsistent (mura), it can lead to the overburdening of people or equipment (muri), which will then cause all kinds of non-value-adding activities (muda).

Value Stream Mapping

Value Stream Mapping (VSM) is used for visualizing the flows of information and materials within a production line, and it provides a map of the current state of the company (Mostafa, Lee, Dumrak, Chileshe & Soltan, 2015). This map shows value-added and non-value-added activities of a production line from raw material to finished product. It is used to identify reasons of wastes and which Lean tools should be used to reduce those wastes (Durakovic, Demir, Abat & Emek, 2018).

Why-Why Analysis

A root cause is the main reason of a problem's existence that, if eliminated or corrected, it would prevent the problem from occurring again (Suárez-Barraza & Rodríguez-González, 2018). A useful tool to find root causes is the Why-why analysis. The why-why analysis starts by stating the problem and asking *why* that problem has occurred. Once the reasons for the problem occurring have been identified, each of the reasons is taken in turn and again the question is asked *why* those reasons have occurred, and so on. This procedure is continued until either a cause seems sufficiently self-contained to be addressed by itself or no more answers to the question 'Why?' can be generated (Slack, Brandon-Jones & Johnston, 2016).

5S

Another tool that might be useful is called 5S, developed by Hiroyuki Hirano as part of the TPS. 5S is the name of a workplace organization method, which uses five Japanese words: seiri (sort), seiton (set), seiso (shine), seiketsu (standardize), and shitsuke (sustain) (Coetzee, Van der Merwe & Van Dyk, 2016). Sort means organizing things in order, and set is designing and clearly labeling where things are stored. Everything should be stored in the right place to eliminate the unnecessary time and energy for searching. Shine is keeping everything clean and neat. Standardize is documenting the work methods and sustain is building a continuous improvement procedures and stick to it (Durakovic, Demir, Abat & Emek, 2018).

Gemba walk

Gemba means 'the actual place where something happens', when translated from the Japanese. This term is often used in Lean Manufacturing to express the idea that in order to understand something, the research should go to the place where it actually happens. This way, problems are made visible, which makes it easier to eliminate waste.

Poka-Yoke

The concept of Poka-Yoke has emerged from the Japanese methods of operations improvement. It involves making processes 'fool-proof', based on the idea that human mistakes are to some extent inevitable. What is important is that they do not lead to defects. Poka-yokes are simple, inexpensive devices or systems that are incorporated into a process to prevent inadvertent mistakes by users (Slack, Brandon-Jones & Johnston, 2016). Examples of poka-yokes are:

- Height bars on amusement riders, to make sure that customers do not exceed size limitations;
- The locks on aircraft lavatory doors, which must be turned to switch the light on;

- The SIM card of a mobile phone that can only be inserted one way.

Visual Management
Visual Management is one of the Lean principles designed to make the current and planned state of the operation transparent to everyone, so that everyone can quickly see what is going on. It usually involves a certain visual sign, such as a screen, a whiteboard, or simply lights that convey what is happening. It seems a trivial and usually simple technique, but Visual Management has several benefits:

- Demonstrate methods for safe and effective working practices;
- Communicate to everyone how performance is being judged;
- Assess at a glance the current status of the operation.

3.2 Theory of Constraints

A central idea of Lean Manufacturing is the smooth flow of items through processes. Any bottleneck disrupts this smooth progress. Therefore, it is important to recognize the significance of capacity constraints in the planning and control process. This is the idea behind the Theory of Constraints (TOC), originally introduced by Goldratt (1984). The TOC, or more appropriately described as the management by constraints, is defined as a management philosophy that focuses on continuous improvement that improves organizational performance (Pacheco, Pergher, Antunes Júnior & Roehe Vaccaro, 2018). TOC is developed to focus attention on the capacity constraints (bottlenecks) of the operation. By identifying the location of constraints, working to remove them, and then looking for the next constraint, an operation always focuses on the part that critically determines the pace of output (Slack, Brandon-Jones & Johnston, 2016).

Just as with Lean Manufacturing, there is a lot of literature about TOC. However, with TOC, there is not as much variation in tools and methods as there is within Lean Manufacturing. As a result, it is easier to get hold of the different important aspects of TOC. Below, we discuss these most important aspects.

The Five Focusing Steps
As a practical method of synchronizing flow, the Theory of Constraints provides the following five steps (Mohammadi & Eneyo, 2012):

1. Identify the current constraint: A constraint is any factor that prevents a system from achieving a higher level of performance than its goal. For this research, the constraint is the single part of the cutting and planing process that causes the most short stops.
2. Exploit the constraint: Make quick improvements to the constraint using existing resources (make the most of what is available).
3. Subordinate the system to the constraint: Review all other activities in the process to ensure that they are aligned with and truly support the needs of the constraint.
4. Elevate the constraint: If the constraint still exists after step 3, consider what further actions can be taken to eliminate it from being the constraint. Normally, actions are continued at this step until the constraint has moved somewhere else. This may result in the acquisition of additional capacity, new machines or new technology to break the constraint. In some cases, capital investment may be required.

5. Repeat: The Five Focusing Steps is a continuous improvement cycle. Therefore, once a constraint is broken or lifted the next constraint should immediately be addressed and step 1 starts again.

Drum, buffer, rope

The Theory of Constraints uses the ‘drum, buffer, rope’ concept (Figure 14) to explain its planning and control approach. According to this concept, there is always a certain part of the process that is acting as a bottleneck on the work flowing through the process. Goldratt (1984) argues that the bottleneck in the process should be the control point of the whole process. It is called the *drum* because it sets the ‘beat’ for the rest of the process. Since the bottleneck does not have sufficient capacity, it should be working all the time. The output of the bottleneck constrains the output of the whole process, so any time lost at the bottleneck affects the output from the whole process. Therefore, it is not worthwhile for the parts of the process before the bottleneck to work to their full capacity. All they would do is produce work which accumulates further along in the process up to the point where the bottleneck is constraining the flow. Therefore, 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. This is called the *rope* (Slack, Brandon-Jones & Johnston, 2016).

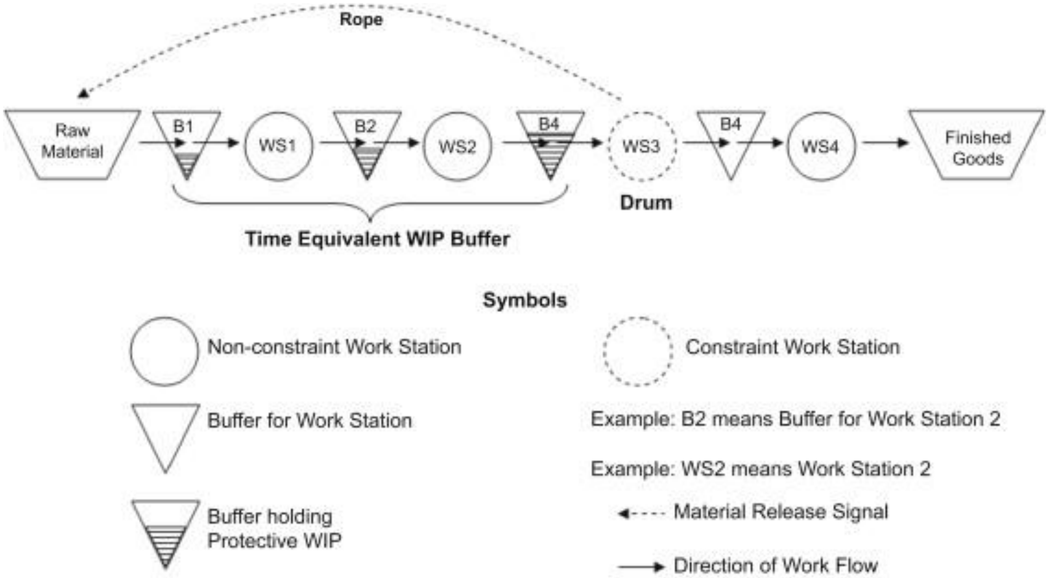


Figure 14: Drum-Buffer-Rope method (Betterton & Cox, 2009)

According to Drum-Buffer-Rope concept, the drum can be optimized by doing the following things (Mohammadi & Eneyo, 2012):

- Developing a detailed schedule for the drum, so that the maximum capacity is not exceeded. This schedule is important since it determines the working speed of the drum and therefore also the pace of the rest of the production process.
- Adding buffers in front and behind the drum to compensate for process variation. This makes the Drum-Buffer-Rope theory very stable and flexible. Since the drum determines the pace of the process, it is important that the drum can always work at its maximum speed, which is only possible if the drum has always material to work with. The buffer in front of the drum can compensate for variation earlier in the process and therefore keep the drum running at its

maximum speed, while a buffer behind the drum ensures that the drum can always keep producing, even if (one of) the processes behind the drum have a failure/breakdown.
- Synchronizing the schedule of all other resources to the drum schedule. This way, the materials are released at the same rate as the drum can process it. The rope gives a sign to the first activity of the production line as soon as the drum process a resource, and then the a new resource is released. The processes behind the drum should also be scheduled to work at the exact same speed of the drum.

3.3 Lean Manufacturing vs. Theory of Constraints

Pacheco et al. (2018) sum up the following main similarities between Lean Manufacturing and the Theory of Constraints:
- Both approaches have the common objective of increasing profits;
- The quality factor is essential for both;
- Both aim at a continuous flow and an increase of capacity;
- Both try to reduce the inventory level to a minimum;
- For both approaches, the workforce plays a relevant role in the development of the method and tools;
- Both offer techniques to control the flow using the concept of pulling the market demand.

Surely, there are also differences between Lean Manufacturing and the TOC. Table 4 shows the biggest differences that are mentioned by Slack, Brandon-Jones & Johnston (2016).

	Lean Manufacturing	**Theory of Constraints**
Overall objectives	To increase profit by adding value from the customers' perspective.	To increase profit by increasing the throughput of a process or operation.
Measures of effectiveness	• Cost • Throughput time • Value-added efficiency	• Throughput • Inventory • Operating expense
How to achieve improvement	By eliminating waste and adding value by considering the entire process, operation or supply network.	By focusing on the constraints (the weakest links) in the process.
How to implement	Continuous improvement emphasizing the whole supply network.	A five-step, continuous process emphasizing acting locally.

Table 4: TOC compared with Lean Manufacturing (Adapted from Slack, Brandon-Jones & Johnston, 2016)

While Lean Manufacturing aims at reducing fixed and variable costs, TOC focuses on the generation of gains rather than cost reduction. The TOC tackles the instability of operation demands using physical- time- or strategic buffers, while Lean Manufacturing constantly tries to reduce the variability. Despite all these differences, there is a substantial overlap between Lean Manufacturing and the TOC. The TOC offers a framework for implementing Lean methodologies, and avoiding the pitfalls of applying them where they are not necessary. Using the TOC as a structure for applying Lean Manufacturing will yield the greatest return for the company. So, the TOC and Lean have evolved into a philosophy of systemic vision, and a hybrid model of both approaches is more productive and easier to implement than one of the two separately (Pacheco et al. 2018). Therefore, in this research we follow this hybrid approach as well. Throughout this research, we execute the Five Focusing Steps, while we have in each step the ability to use the various tools of Lean Manufacturing.

3.4 Chapter conclusion

The research question for this chapter was as follows:

"What literature is useful for eliminating short stops?"

We answered this research question by answering the following two sub-questions:

a. Which techniques exist to identify the root causes of short stops?

Identifying the constraint that is the root cause of most short stops is the first step of the Five Focusing Steps from the Theory of Constraints and during this step, we use various principles of Lean Manufacturing. First, we compose an Ishikawa diagram in Chapter 4 that proposes possible causes for short stops. We find those causes based on interviews with operators, and from observations during our own Gemba walks on the work floor. Once a proposed root cause is confirmed by means of data, we use the Why-Why Analysis to find the underlying reasons for the existence of this root cause.

b. What is the best approach to eliminate short stops?

In order to find the best improvement strategy that eliminates short stops, we execute steps 2, 3 & 5 of the Five Focusing Steps from the Theory of Constraints. Within this structure, we use again some of the aforementioned Lean Manufacturing principles, depending on what the root causes turn out to be.

4

Root cause identification

The aim of this chapter is to execute the first of the Five Focusing Steps from the Theory of Constraints: identifying the constraint of the system. Executing this step answers the following research question:

"What causes the short stops?"

Before we identify the actual constraint, we first search for symptoms of the problem, which are then traced back to the root cause, the underlying problem. In Chapter 3 we discussed the Ishikawa diagram as a particularly effective method of helping to search for the root cause of a problem. This diagram identifies areas where further data is needed, and these areas are often categorized under the headings of: man, machine, material, method, milieu and measurement. Yet, in practice, any categorization that comprehensively covers all relevant possible causes could be used (Slack, Brandon-Jones & Johnston, 2016). Based on interviews with the operators, we found that the possible causes for short stops belong to the categories man, material, machine & method. Cierpa (n.d.) mentions these four categories as the most common causes for short stops as well. Therefore, we use these categories as the basis for this chapter. The Ishikawa diagram in Figure 15 shows for each category the causes that could possibly influence the occurrence of short stops. We investigate in this chapter if we can prove the influence of each possible cause based on data, by showing the relationship between each possible cause and the number of short stops per kilometer output in a scatter diagram. This is a sophisticated way of quantifying how strong the relationship between two variables is (Slack, Brandon-Jones & Johnston, 2016). This chapter concludes with a section that summarizes the previous sections, and mentions the biggest constraint of the system which is the root cause of most short stops.

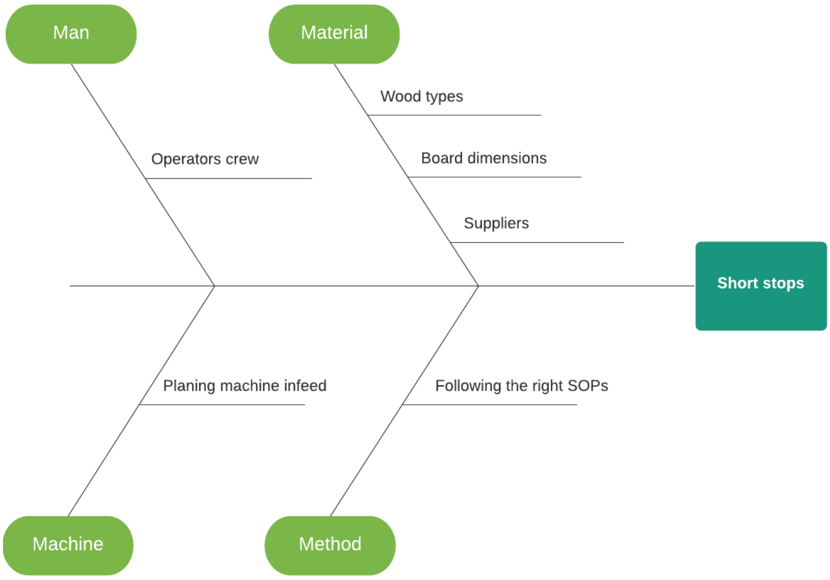


Figure 15: Ishikawa diagram with possible causes for short stops

4.1 Man

This section investigates whether there exists a relationship between the crew that is working, and the occurrence of short stops. There are two separate crews who control the cutting and planing line: the green- and the blue team. Every day, one crew works the early shift (6:00 AM – 2:00 PM), and the other crew works the late shift (2:00 PM – 11:45 PM). Evidently, the late shift is longer than the morning shift but every week, the crews change the shift that they are working so in two weeks, both crews have equally much working hours. During a shift, two operators control the cutting and planing line. They try to prevent the occurrence of production problems, and solve the problems that still occur. Their handling speed determines how fast those problems are solved, and hence how fast the line can continue producing. Obviously, the operators have a huge influence on the productivity of the line. In case there is a difference between the performance of both crews with regard to the occurrence of short stops, it can mean that the crew that has the worst performance does not follow the Standard Operating Procedures (SOPs), or that they are not paying enough attention, for example. Before we can say anything about a relationship between the crews and short stops, we have to find out for both crews how many short stops occur during their shifts. Based on the batch identification number, we can see in the database of Phoenix which batch is processed by which crew, so combining the production logs, Gantt charts and the database enables us to calculate the number of short stops per crew. For example, Table 5 shows what this looks like for the first working day of 2021, and doing these calculations for every shift between January 2020 and April 2021 results in Figure 16.

Shift	Crew	* Output (m)	* Short stops	SS/km
Morning	Blue	73,972	76	1.03
Late	Green	73,575	23	0.31

Table 5: Short stops for each crew on January 4, 2021

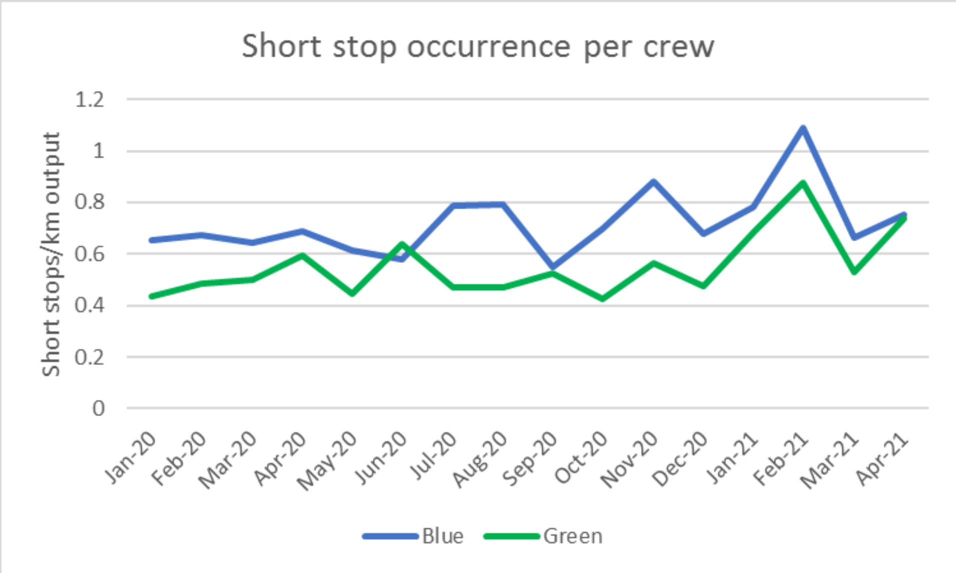


Figure 16: Short stop performances of both crews

In Figure 16, the blue and green lines represent the blue crew and the green crew, respectively. In this figure, we notice again the peak in February 2021 that we noticed in Chapter 2 before. It turns out that this peak exists for both crews, so the peak is not caused by one of the crews. However, there is an obvious difference with regard to the performance of both crews in general. Since the beginning of 2020, the green crew incurred 0.55 short stops per kilometer output, and the blue crew 0.72. So, when the blue crew is working, the number of short stops per kilometer increases by 31.3%, which is a significant difference. Apparently, both crews do their job in a different way. This means that the difference between the two crews is a consequence of a real root cause: the work method. Section 4.4 elaborates on this as the last bone in the Ishikawa diagram.

4.2 Material

The used material can also have a huge influence on the performance of the cutting and planing line. The line processes a high variety of boards: their dimensions differ from each other, but also the kind of wood the board is made of, and the quality is different from board to board as well. Based on the batch identification number, we can find out all these material properties for each batch in the database of Phoenix. In this section, we investigate the influence of the material properties on the occurrence of short stops.

4.2.1 Wood

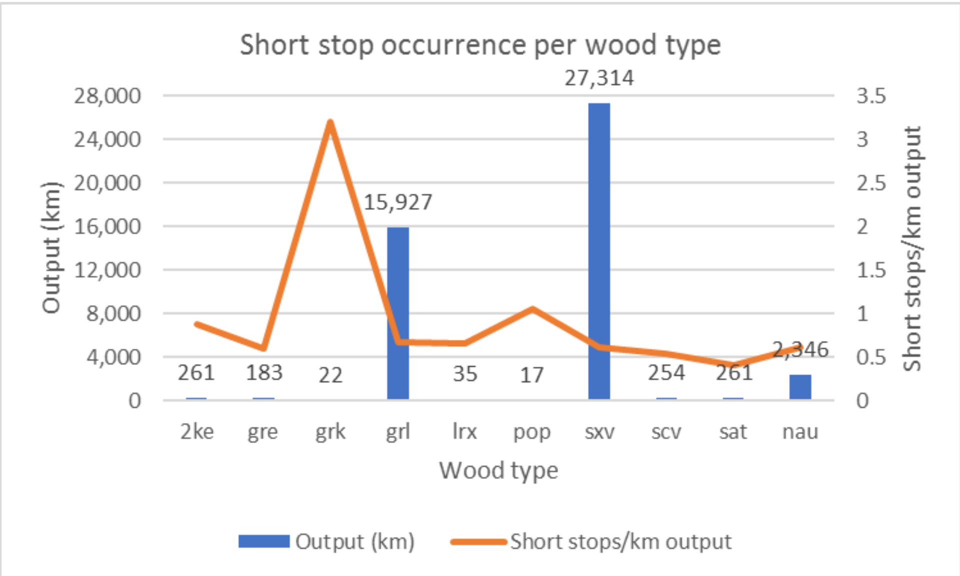
Wood types

Sometimes, a short stops occurs when a board is removed from the line because it is for example broken or crooked. In order to get more insight in the phenomenon ‘bad wood quality’, this section compares the different wood types to test the influence of the wood type on the occurrence of short stops. We can find for each batch the wood type in the database based on the batch identification number. The wood type can be indicated with 11 different codes, Table 6 lists these codes and what they mean.

Wood code	Meaning
2ke	Second choice spruce wood, very bad quality.
gre	Untreated whitewood.
grb	Treated whitewood.
grk	Whitewood used for the legs of a pallet.
grl	Long whitewood boards.
lrx	Larch wood.
pop	Poplar wood.
sxv	Sextra spruce wood, which means spruce wood with a normal amount of wane.
scv	Schaalboard spruce wood, which means spruce wood with a lot of wane.
sat	Sxv wood, processed for customer Satim.
nau	Sxv wood, processed for customer Naus.

Table 6: Wood codes and their meaning

Based on the production logs, Gantt charts and database, we know for each day which wood types the cutting and planing line processed during that day, and how many short stops happened when doing so. Not every wood type is used as much as the other. * Figure 17 shows how much of each wood type is processed since the beginning of 2020, as well as the number of short stops that occur per kilometer output. Since the wood type 'grb' has not been produced at all since the beginning of 2020, this wood type is not included in * Figure 17.



** Figure 17: Short stop occurrence per wood type since the beginning of 2020*

Grk
On average, 0.63 short stops occur per km output. With that in mind, a few things stand out when looking at * Figure 17. First, the number of short stops/km output is extremely high for the wood type 'grk'. To find out why this is the case, we combine the production logs, Gantt charts and database to show all batches with 'grk' wood in Table 7.

Batch id	Crew	Wood	Length (cm)	Width (mm)	Thickness (mm)	* Output (m)	* Short stops	Ss/km
515	Green	grk	3,600	98	78	1,276	5	4.17
1,631	Blue	grk	4,000	98	78	1,716	9	5.17
1,632	Blue	grk	3,000	98	78	1,287	0	0
2,144	Green	grk	4,000	78	78	4,630	7	1.53
3,416	Blue	grk	3,000	78	78	2,021	9	4.39
3,416	Green	grk	3,000	78	78	10,635	39	3.67

Table 7: All batches with wood type 'grk' since January 2020

What each 'grk' batch has in common, is the board thickness of 78 mm. This thickness is much higher than the normal thickness of boards, which is usually between 16 mm and 22 mm. This makes sense, because Table 6 already mentioned that the purpose of 'grk' wood is to produce the legs of the pallets, and the legs of a pallet need to be a lot thicker than the normal boards. In Section 4.2.4, we investigate whether the board thickness really impacts the occurrence of short stops, and if this material property is the reason why the number of short stops/km is relatively high for 'grk' wood. However, it is good to keep in mind that the output for 'grk' wood was only 22 km since the beginning of 2020, which can make the data less reliable.

2ke

Next, the value for '2ke' is higher than average as well. This is something that was already expected by the company, because this wood is considered to be second choice (see Table 6). The company bought this wood type relatively cheap, because it was over one year old which makes the wood really weak. As a result, incidents like a broken board happen more often, which is why the number of short stops increases.

Pop

The last wood type where short stops occur more frequent than the average is the poplar wood. Just like the '2ke' wood, poplar wood is soft wood, so the reason for the high frequent occurrence of short stops is the same as for the '2ke' wood. Again, it is important to keep in mind that only 17 km of poplar wood has been processed since the beginning of 2020, which reduces the reliability of the data.

Sxv vs. Grl

All the aforementioned wood types are only processed occasionally. To test whether the wood type really influences the number of short stops, we compared the two most used wood types: 'sxv' & 'grl'. Figure 18 shows the result of this comparison.

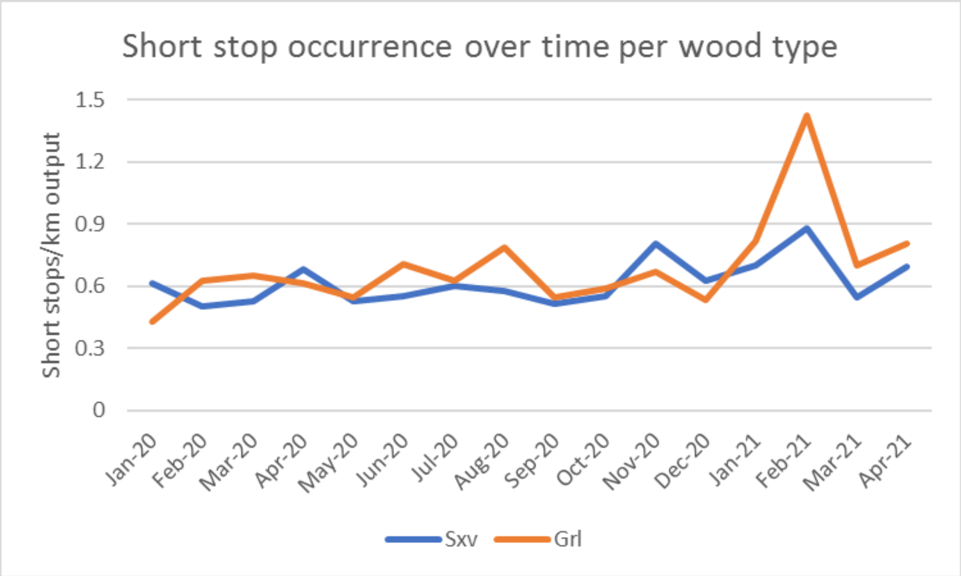


Figure 18: Short stop occurrence over time for two wood types

We notice from Figure 18 that the occurrence of short stops is almost equal for both wood types in entire 2020. However, there is a big difference in February 2021. In this month, ‘grl’ had much more short stops/km than ‘sxv’. That sounds familiar, since we noticed this peak in Chapter 2 as well. Now we know that this peak is caused by the wood type. It turns out that February 2021 was a real winter month with snow and ice. Next to that, ‘sxv’ packages are covered with plastic, while ‘grl’ packages are exposed to the weather circumstances. In practice, this means that ‘sxv’ packages are dry, and ‘grl’ packages are wet because of rain, hail and snow. When it is freezing, like in February 2021, wooden boards in ‘grl’ packages stick together and separating them manually during the production process often takes a short stop. So, the weather circumstances combined with a specific wood type caused the high peak in February 2021 that we saw in Chapter 2. If it is not freezing, however, the wood type does not really have an influence on the number of short stops because in 2020, a year without any serious frost, the difference between grl wood and sxv wood was negligible: 0.62 and 0.58 short stops/km output respectively. So, the wood type is not a root cause for short stops.

4.2.2 Length

One of the operators has the impression that more short stops happen when the line is processing short boards. To investigate whether this is true or not, we use again the aforementioned production logs, Gantt charts and database. Combining these three data sources gives us the results from Table 8, based on the production between January 2020 and April 2021.

Board length (cm)	* Output (km)	* Short stops	Ss/km	Board length (cm)	* Output (km)	* Short stops	Ss/km
2,400	277	532	1.93	**4,000**	5,108	3,252	0.64
2,500	191	317	1.65	**4,100**	578	512	0.89
2,700	567	876	1.54	**4,200**	2,497	1,494	0.60
2,800	14	12	0.92	**4,260**	826	450	0.54
2,985	14	0	0	**4,500**	4,348	2,432	0.56
3,000	3,919	4,144	1.06	**4,560**	5	2	0.33

3,060	193	277	1.42	**4,800**	3,804	1,854	0.49
3,100	138	126	0.91	**4,860**	2,042	886	0.43
3,300	1,097	962	0.88	**4,900**	2	7	3.58
3,400	4	5	1.30	**5,000**	7,047	3,538	0.50
3,500	94	64	0.68	**5,100**	3,201	1,287	0.40
3,600	2,575	2,076	0.81	**5,400**	2,304	1,009	0.44
3,650	32	2	0.06	**5,460**	216	69	0.32
3,660	544	436	0.80	**5,500**	2	0	0
3,700	510	388	0.76	**5,700**	955	408	0.43
3,900	2,411	1,510	0.63	**5,980**	25	9	0.36
3,980	55	30	0.54	**6,000**	1,897	968	0.51

Table 8: Short stops per kilometer output for all board lengths

Figure 19 shows the results of Table 8 in a graph. Clearly, there are some outliers in Figure 19. These outliers exist because they are based on an output of only a few kilometers. To make the results as reliable as possible, we choose to remove all board lengths with less than 90 km output since the beginning of 2020. Figure 20 shows the graph without these outliers. We notice from Figure 20 that for boards shorter than approximately 4,500 cm, the impact of the board length on the occurrence of short stops is significant, while for boards longer than 4,500 cm the differences in performance between board lengths is quite small. It is interesting to find out why short boards cause more short stops than long boards. The operator who came earlier with the suggestion that this difference exists, is convinced that it is caused by the second separator. Section 4.3 elaborates on this hypothesis.

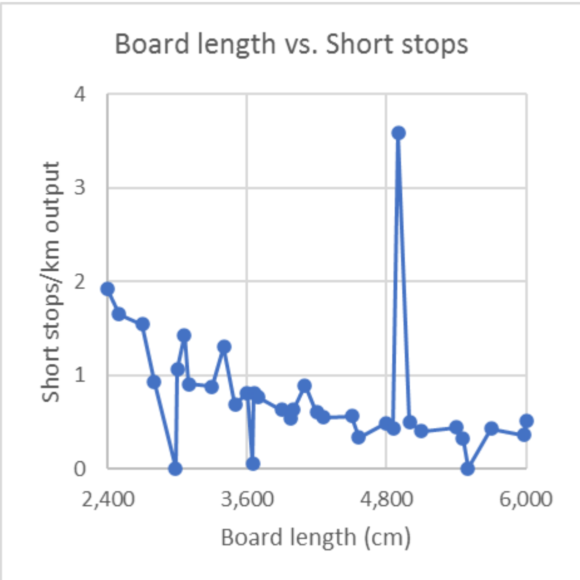


Figure 19: Relationship board length and short stops

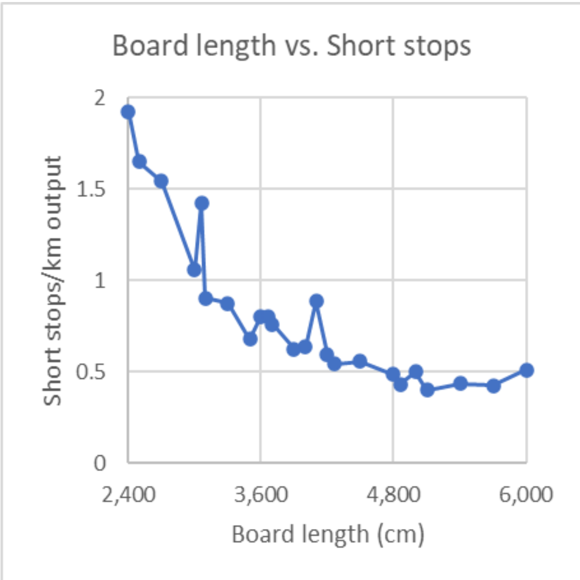


Figure 20: Board length vs. short stops without outliers

4.2.3 Width

In order to determine the influence of the board width on the occurrence of short stops, we follow the same procedure as we did in Section 4.2.3, but now the variable is the board width. This procedure yields the results of Table 9, based on the production since the beginning of 2020.

Board width (cm)	* Output (km)	* Short stops	Ss/km	Board width (cm)	* Output (km)	* Short stops	Ss/km
8	23	16	0.68	**98**	8,198	5,124	0.63
10	16	5	0.34	**99**	1,159	484	0.42
15	4	4	0.84	**100**	11,367	6,498	0.57
43	9	9	0.93	**102**	257	381	1.48
45	16	18	1.06	**118**	333	190	0.57
48	14	16	1.07	**125**	5,620	3,281	0.58
50	27	18	0.65	**133**	12	21	1.79
75	11,049	7,191	0.65	**135**	2	4	1.74
76	5	2	0.31	**140**	39	27	0.68
78	737	629	0.85	**143**	4,071	2,985	0.73
89	30	18	0.57	**145**	1,446	874	0.60
95	1,632	1,099	0.67	**150**	1,384	1,021	0.74
97	28	21	0.73				

Table 9: Short stops per kilometer output for all board widths

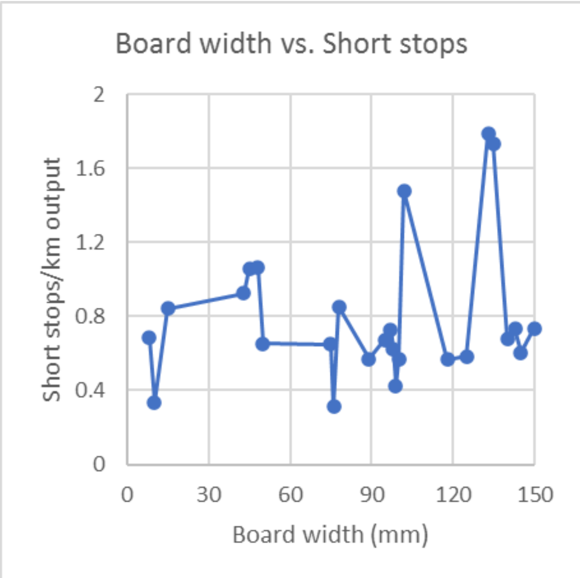


Figure 21: Relationship board width and short stops

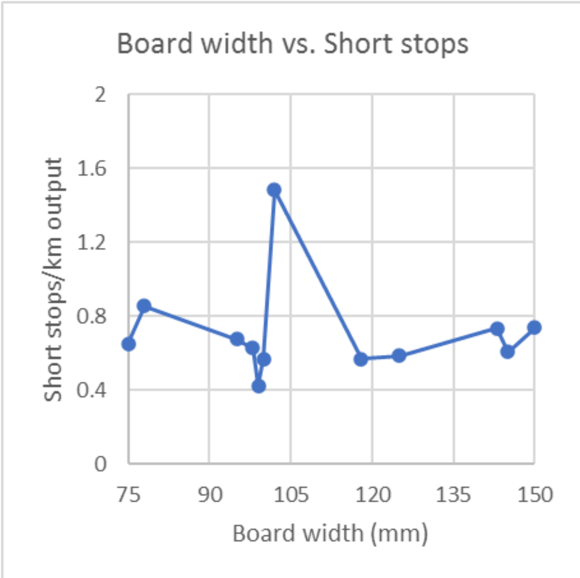


Figure 22: Board width vs. short stops without outliers

Figure 21 represents the results of Table 9 in a graph, and Figure 22 is what is left over after removing outliers with less than 90 km output in 14 months, just like we did in Section 4.2.3. Based on Figure 22, we conclude that there is no proof for a relationship between the board width and the number of short stops that occur. The only thing that is remarkable, is the high peak for board width 102 mm. This datapoint is calculated based on 257 km output, so we do not think this peak exists because we used insufficient data. To find out what does cause this peak, we create Table 10 which shows all batches that are processed since the beginning of 2020 where the board width is 102 mm.

Batch id	Crew	Wood	Length (cm)	Width (mm)	Thickness (mm)	* Output (m)	* Short stops	Ss/km
98	Green	sxv	4,000	102	51	11,230	9	0.79
99	Green	sxv	4,000	102	51	16,165	30	1.86

102	Blue	sxv	4,000	102	51	851	0	0
103	Blue	sxv	3,000	102	51	404	0	0
543	Green	sxv	4,000	102	51	23,815	19	0.82
706	Blue	sxv	4,000	102	51	11,053	11	0.96
707	Blue	sxv	3,000	102	51	12,634	19	1.54
708	Blue	sxv	3,000	102	51	12,150	27	2.19
827	Green	sxv	4,000	102	51	8,082	19	2.41
1,039	Blue	sxv	3,000	102	51	15,761	25	1.57
1,056	Green	sxv	4,000	102	51	26,225	25	0.95
1,157	Green	sxv	4,000	102	51	22,078	23	1.04
1,158	Green	sxv	3,000	102	51	7,646	23	3.01
1,286	Blue	sxv	4,000	102	51	14,463	7	0.49
1,718	Green	sxv	4,000	102	51	23,793	27	1.12
1,818	Blue	sxv	3,000	102	51	9,635	21	2.21
2,388	Green	sxv	4,000	102	51	10,209	18	1.74
2,389	Green	sxv	4,000	102	51	4,686	14	3.03
3,211	Green	sxv	3,000	102	22	6,381	14	2.22
3,212	Green	sxv	3,000	102	22	2,552	5	2.08
3,255	Blue	sxv	4,000	102	51	4,956	16	3.22
3,251	Blue	sxv	3,000	102	51	5,870	7	1.21
3,261	Blue	sxv	3,000	102	51	6,881	21	3.09

Table 10: All batches with board width 102 since January 2020

The first thing that is remarkable, is that all boards with board width 102 mm that are processed on the cutting and planing line since the beginning of 2020, are boards of wood type ‘sxv’. However, Section 4.2.1 showed already that the wood type does not significantly influence the occurrence of short stops, so the wood type cannot be the reason for the high peak in Figure 22. Next, we see that the thickness of almost all batches is 51 mm, which is considerably higher than the average board thickness because the thickness of most boards is between 16 mm and 22 mm. In Section 4.2.1, we also did the suggestion that a large board thickness can increase the number of short stops per kilometer output, so we test in Section 4.2.4 whether this hypothesis is true.

4.2.4 Thickness

Similar to how we calculated our results for the board length and board width, we use the production logs, Gantt charts and database to calculate the influence of the board thickness on the number of short stops. Table 11 shows the results of these calculations based on the production since the beginning of 2020, and Figure 23 represents these results graphically. After removing outliers with less than 90 km output, we get Figure 24.

Thickness (cm)	* Output (km)	* Short stops	Ss/km	Thickness (cm)	* Output (km)	* Short stops	Ss/km
9	5	4	0.67	**28**	124	131	1.06
14	154	175	1.13	**32**	9	11	1.20
15	346	238	0.69	**46**	14	34	2.25
16	11,645	7,159	0.61	**50**	7	11	1.63

17	4,080	3,109	0.76	**51**	268	385	1.43
18	138	64	0.46	**75**	69	87	1.27
19	6,503	3,423	0.53	**78**	35	105	2.91
20	18	2	0.1	**95**	21	30	1.37
21	291	140	0.48	**96**	9	4	0.37
22	23,248	14,543	0.62	**100**	27	18	0.65
25	479	264	0.55				

Table 11: Short stops per kilometer output for all board thicknesses

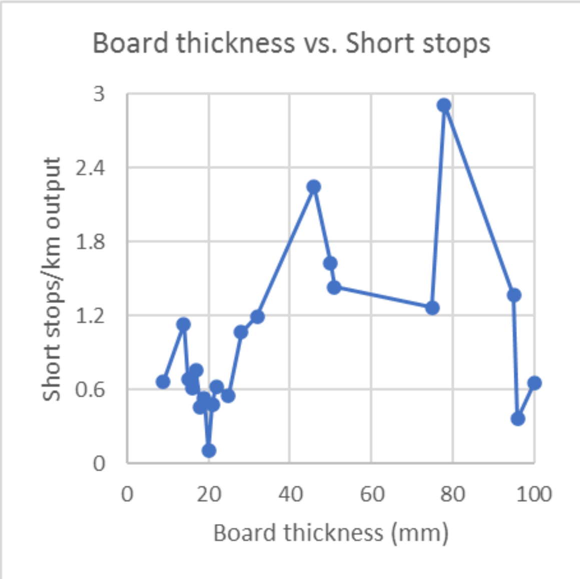


Figure 23: Relationship board thickness and short stops

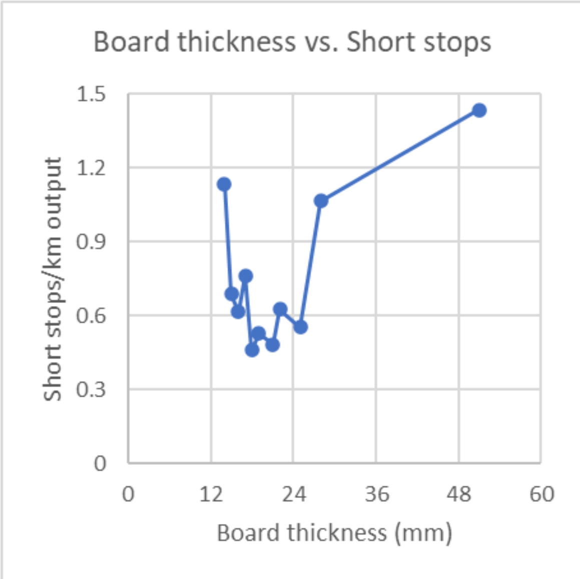


Figure 24: Board thickness vs. short stops without outliers

Based on Figure 24, there seems to be an optimal board thickness, somewhere between 15 mm and 25 mm. Since the beginning of 2020, 98.4% of all boards were between 15 mm and 25 mm thick. Apparently, the cutting and planing line is most suitable for these board thicknesses, but sometimes it needs to process boards that do not fall within those boundaries. This does explain the peaks in * Figure 17 for wood type 'grk' and in Figure 22 for board width 102 mm, but since thick boards are almost never processed the board thickness cannot be considered as a root cause for short stops.

4.2.5 Supplier

Section 4.2.1 already showed mentioned that some short stops occur because of bad wood quality. These short stops occur when the board is removed from the line because the quality is too low to process further, or when an incident occurs due to the nature of the wood. The latter case mostly occurs with boards that have a lot of wane, because these boards can easily slide on top of each other because of their round corners. Figure 25 shows the most occurring wood defects.

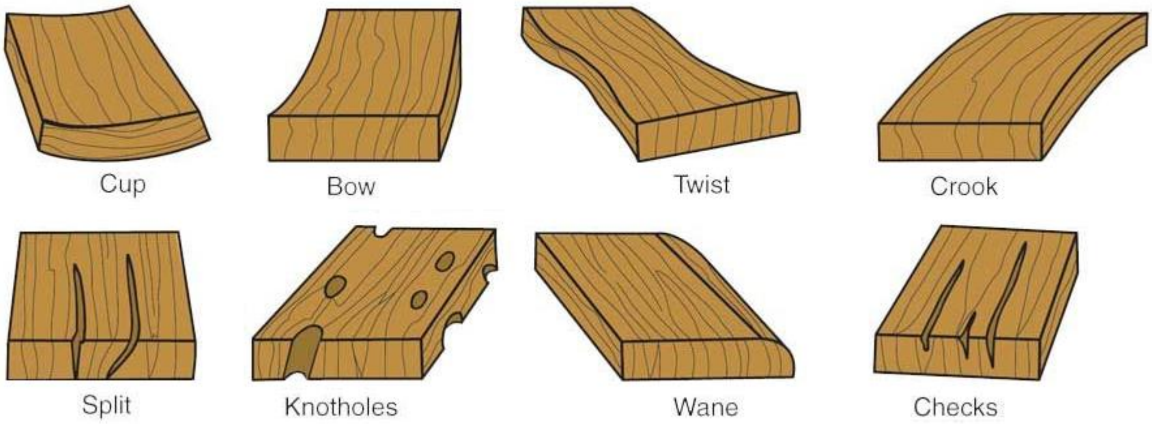
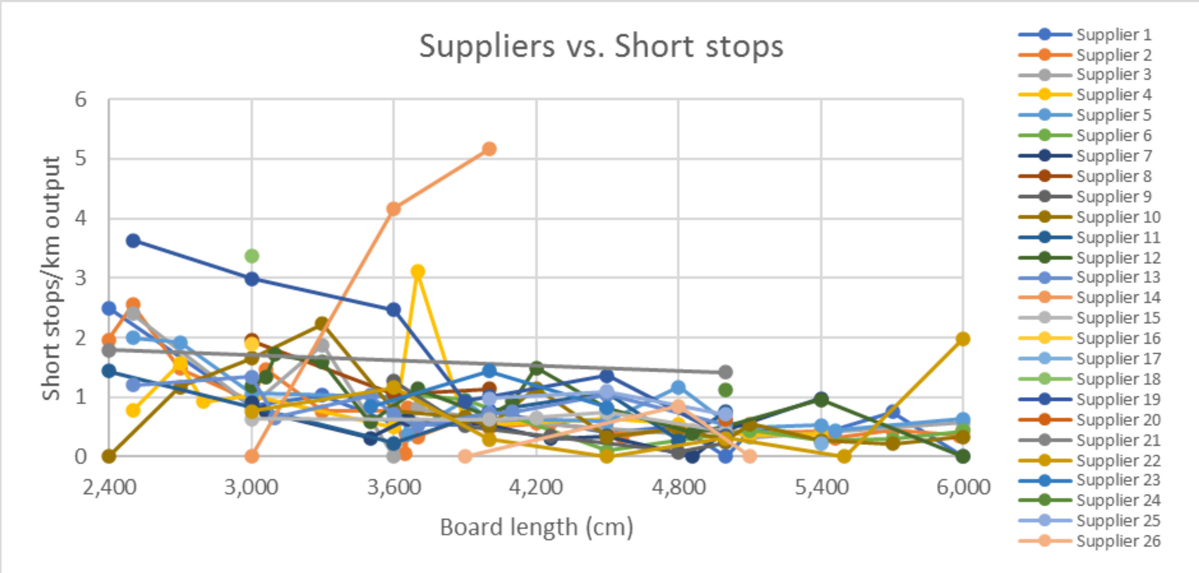
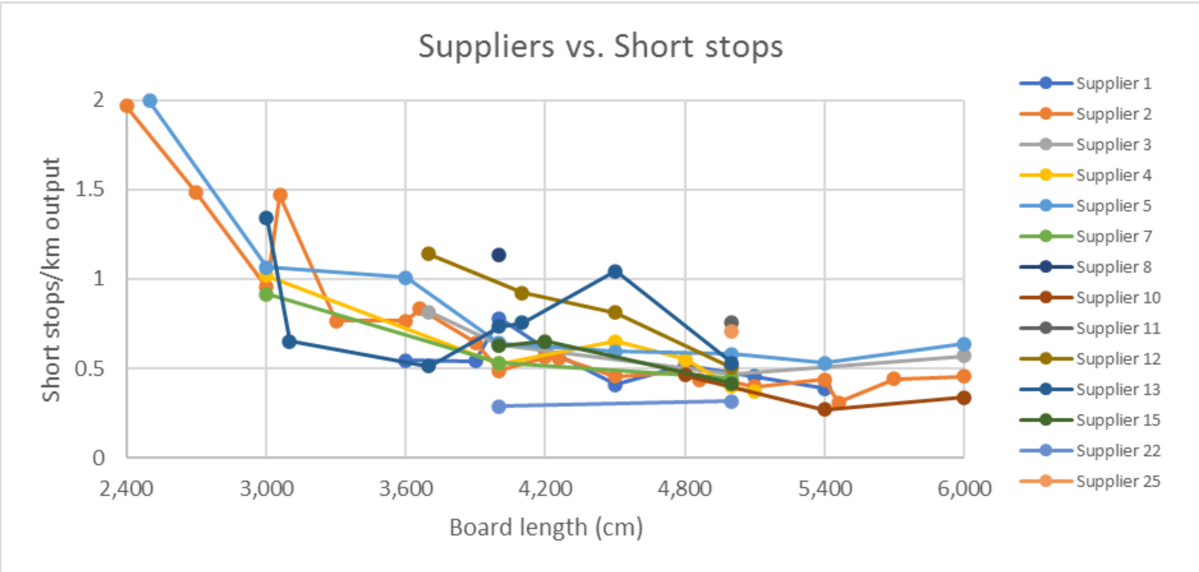


Figure 25: Most occurring wood defects (Sherwood Lumber, n.d.)

As will become evident in Section 4.3, bad wood quality only causes a very small share of all short stops, so it cannot be considered as a root cause for short stops. Still, it might be interesting to investigate if the company can avoid these short stops. If the wood from a certain supplier constantly causes more short stops than average, it might be an option to reconsider purchasing wood from that supplier. Based on the production logs, Gantt charts and database, we calculate for each supplier that has delivered wood to Phoenix since the beginning of 2020 how much short stops occurred on average per board length. The reason why we choose the board length as a second independent variable is because Section 4.2.2 showed that the board length has a huge influence on the occurrence of short stops, so adding the board length as a second independent variable eliminates the possibility that a supplier seems to deliver a lot of bad wood, while in reality they deliver relatively a lot of short boards. Figure 26 shows the results of these calculations. This figure contains many datapoints based on only a few kilometers output, which makes these datapoints not very reliable. Therefore, we remove all datapoints that are based on less than 90 km output. * Figure 27 shows the results without these datapoints. In this figure, no supplier stands out which means that none of the suppliers deliver such bad wood that it causes significantly more short stops. Due to confidentiality reasons, the real names of the suppliers are anonymized in Figure 26 and in * Figure 27.



** Figure 26: Relationship between suppliers and the occurrence of short stops*



** Figure 27: Relationship between suppliers and the occurrence of short stops without outliers*

4.3 Machine

When a short stop occurs, something happened at a certain part of the production line. Before we can find the root causes of these events, it is important that it is first clear what exactly happened that resulted in a short stop, which is what we find out in Section 4.3.1. Next, we investigate in Section 4.3.2 in depth the event that comes in Section 4.3.1 forward as the biggest constraint of the cutting and planing line.

4.3.1 Counting

Most of the times, the operators know what happens during these moments based on their experience. A data collection method has to be found in order to turn this tacit knowledge into explicit knowledge. This is possible by interviewing the operators, and asking them to list all the possible causes for short stops that they know. However, this data collection method only gives a list of events, but it does not say something about the frequency of each event's occurrence. Therefore, after collecting a list of possible causes, we ask the operators to count how often each event occurs within a timeframe of two weeks. This way, we can discover the constraint of the cutting and planing line.

Possible causes
The operators came up with the following list of events that cause short stops:

1. De-stacker idling:
   All the wood on the line is currently processed, and a new package of wood has not arrived yet, so the line needs to wait a moment.
2. De-stacker sensor:
   This sensor is covered with sawdust, and as a result the sensor cannot notice anything anymore. The sensor should be cleaned first, before production can continue.
3. De-stacker sticks:
   The packages of wood have between certain amounts of layers intermediate sticks for stability. If something goes wrong with the disposal of these sticks, production stops for a short moment.
4. Infeed idling:
   The second separator, which supplies the infeed, cannot keep up with the speed of the planing machine, so the infeed and hence the planing machine is idling for a moment.
5. Infeed double board:
   Two boards arrive on top of each other at the infeed. The infeed can only process one board at a time, so the top board has to be removed manually by one of the operators, which causes a short stop.
6. Planing machine sensor:
   The sensor is covered with sawdust, which means that the sensor does not notice it when the planing machine is ready to receive a new board so production stops. Cleaning this sensor results in a short stop.
7. Planing machine board:
   When a board breaks in the planing machine, this board has to be removed, and the required procedure with entering through a safety door often takes a short stop.
8. Slowdown belt failure:

The slowdown belt has the purpose of giving boards from the planing machine to the next step in the process. If a board is crooked, the slowdown belt has difficulty transporting this board so it should be removed manually.

9. Stick dropper failure:
   The part that puts intermediate sticks between the layers of wood that has been processed does not work. While the operators fix this issue, the line is not producing so if they can fix it almost immediately, this event causes a short stop.
10. Ice:
   Due to the weather outside, it is possible that boards within a package are frozen to each other. Before these boards can be processed, they have to be separated manually by one of the operators. If this action takes less than 45 seconds, it counts as a short stop.
11. Bad wood:
   A board somewhere on the line has to be removed because it is for example crooked or broken. To do so, the operator has to go through a safety door which takes some time, and sometimes this results in a short stop.

Counting results

The occurrence of each event is counted by one operator during his shifts between March 8 and March 18. During these shifts, he counted 226 short stops (Table 12), while in reality, there occurred 337 short stops. This means that the operator was able to keep track of 67.1% of all short stops that occurred during the counting period. The other short stops were for example lost because the operator was busy with something more urgent, or because he went away for a quick bathroom break. Assuming that he did not miss any short stops due to the nature of that specific short stop, the counting results can be considered as a good representation of reality. Table 12 shows the results of the two counting weeks.

Event	8-3	9-3	10-3	11-3	12-3	15-3	16-3	17-3	18-3	Total
De-stacker idling	2	3	3	6	2	3	2	3	2	**26**
De-stacker sensor	1	2	1	1	0	1	2	2	2	**12**
De-stacker sticks	0	0	0	6	0	0	0	0	0	**6**
Infeed idling	10	7	6	20	12	8	8	11	16	**98**
Infeed double board	1	2	1	2	1	2	1	2	0	**12**
Planing machine sensor	3	2	3	1	0	6	2	1	1	**19**
Planing machine board	2	1	2	0	0	0	0	0	0	**5**
Slowdown belt failure	6	3	3	2	2	3	2	3	1	**25**
Stick dropper failure	2	2	3	1	2	1	1	2	1	**15**
Ice	2	0	0	0	0	0	0	0	0	**2**
Bad wood	0	0	0	0	0	0	0	0	6	**6**

Table 12: Counting results

Figure 28 shows the counting results in a pareto diagram. During the counting weeks, two short stops occurred because boards were frozen to each other, and they had to be separated manually by one of the operators. It is good to take into account that this event depends a lot on the weather circumstances, so if the operator counted the short stops a few weeks later, there probably would not be any boards frozen to each other anymore. The pareto in Figure 28 clearly shows that the main problem is that the second separator often cannot keep up with the speed of the planing machine, because this event is responsible for 43.4% of all counted short stops, which makes the second separator the constraint of the cutting and planing line. Due to the limited available time for this research, this research focuses from now on solely on this constraint.

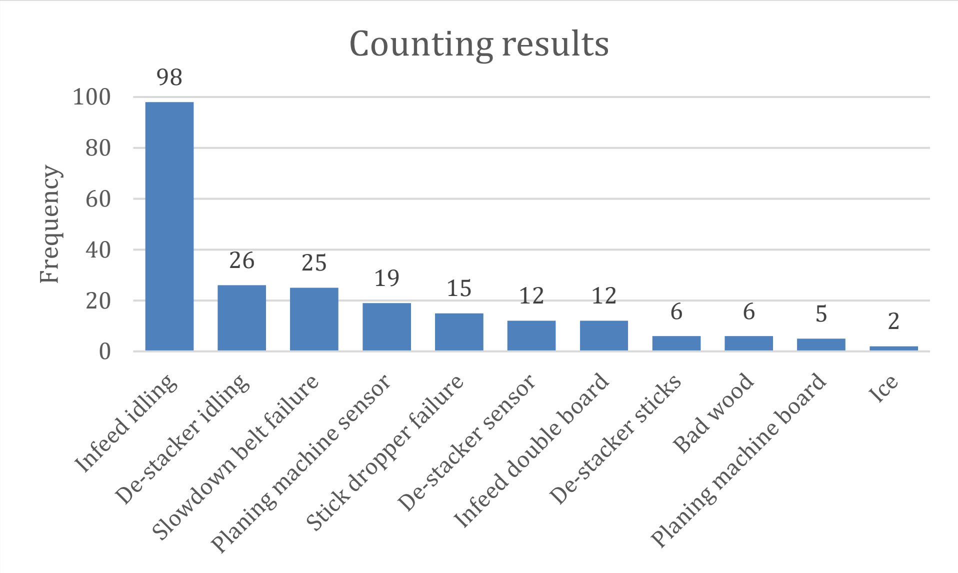


Figure 28: Counting results pareto

4.3.2 Infeed idling

Separator speed

Before we can find the root cause(s) why the infeed is idling so often, we first explain a bit more about this event. The second separator delivers the boards in transverse direction, and the planing machine processes these boards in longitudinal direction. This way, the required speed of the separator depends on the length of the board and the speed of the planing machine. For example, planing 200 meters of wood per minute in boards of 2.5 meter requires the separator to deliver 80 boards/min, while this is only 40 boards/min when the board length is 5 meters. Figure 29 shows whether the average speed of the separator is high enough to prevent the planing machine from idling. The four lines represent the required separator speed for four different planing speeds, and the colored areas show if these required separator speeds are achieved in practice.

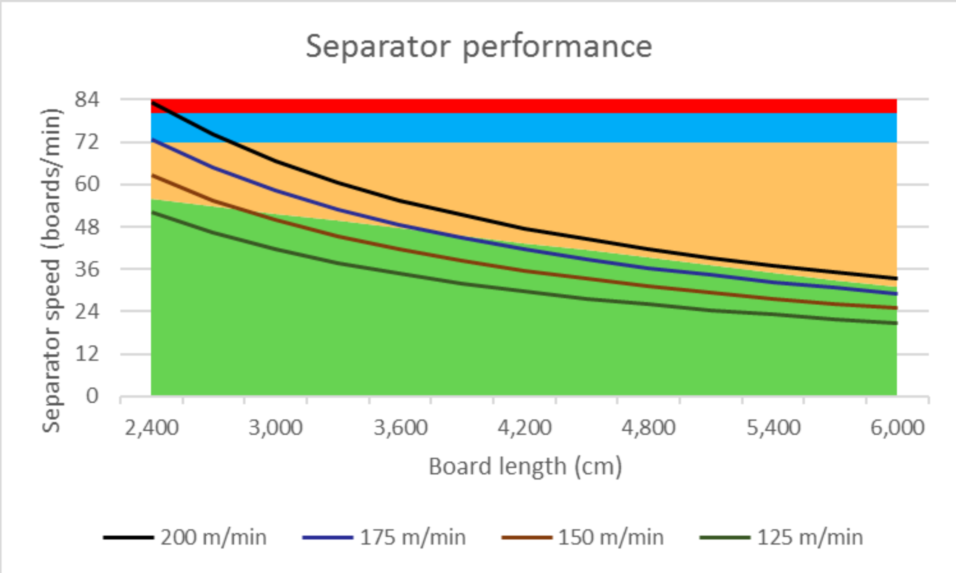


Figure 29: Separator performance for different planing speeds

In Figure 29, all speeds above 80 boards/min are colored red, because according to the manufacturer of the separator, the top speed of the separator is 80 cycles/min. This means that planing at 200 m/min requires the separator to deliver more than 80 boards per minute for certain board lengths, and the separator cannot meet this demand, which is why the planing machine is idling sometimes. To check if our separator is able to reach the promised number of 80 cycles/min, we asked the operator to put the separator speed on maximum for one minute, and then counted the number of cycles that were processed during that minute. It turns out that the top speed is only 72 cycles/min. Therefore, values between 73 and 80 are colored blue in Figure 29, which means that the separator should be able to reach that speed, but fails to do so in practice. Next, speeds that are smaller than or equal to 72 boards/min, and higher than the average separator speed, are colored yellow in Figure 29. This color means that the separator should technically be able to reach the corresponding speeds, but for some reason these speeds are not reached on average. In other words, despite the fact that the separator runs at 72 cycles/min, it does not deliver 72 boards/min to the planing machine. Apparently, cycles/min ≠ boards/min. Below, we explain why this phenomenon occurs. Lastly, the green area in Figure 29 represents all speeds below the average separator speed, so the separator has no problem reaching these speeds. To summarize, if the required separator speed is below the average separator speed, the planing machine will not be idling. If the required separator speed is above the average separator speed, the three different colors indicate why this results in an idling planing machine.

Cycles/min ≠ boards/min

As mentioned above, the yellow area in Figure 29 means that when working at top speed (72 cycles/min), the separator should be able to prevent the planing machine from idling when processing the corresponding board lengths, but fails to do so in practice. There is a clear reason why this keeps occurring: not every pocket is filled with a board. This happens when the single feed unit does not release a board when a new pocket is passing by. The reason why the single feed unit does not release a new board is because the buffer in front of the single feed unit is too small. Before the first board of the buffer can be released, the buffer should consist of a certain amount of boards, based the width of the boards. This is necessary, because having a buffer of a few boards before the first one can be released ensures that the first one lies still at the moment of release. This means that in order to fill every pocket on the second separator, we have to make sure that the buffer in front of the single feed unit is at all times large enough. Chapter 5 investigates how this can be realized.

Board length

Section 4.2.2 ended with the comment that according to one of the operators, the differences in short stop occurrence between the board lengths is caused by the second separator. This section proved that this hypothesis was right, and that the second separator is indeed the reason why the infeed is idling so often. This means that the second separator is the constraint of our system, and the following three root causes are the reason why this separator is the constraint:

- For some combinations of board length and planing speed, the separator needs to work harder than its technical capacity of 80 cycles/min;
- The separator should technically be able to reach 80 cycles/min, but only achieves 72 cycles/min;
- The buffer in front of the single feed unit is often too small, which is why not every pocket on the separator is always filled with a board.

4.4 Method

We noticed during our observations on the work floor that the operators have slightly different work methods, especially regarding how they control the different components. The cutting and planing line is fully automatic, which means that it is equipped with many sensors that bring the components in motion when necessary. For example, when the buffer after the de-stacker is getting empty, this is noticed by a sensor and based on this signal the de-stacker lifts a little bit more in order to fill the buffer again. The disadvantage of automatically controlled components is that a sensor can react on current situations, but it is impossible for them to anticipate on future situations. All the components can also be controlled manually, which means that the operator decides when the components are brought in motion. Operators have the ability to see a certain situation coming, and to take the required measures on time. Section 5.3.1 gives a practical example of such a situation, where the insight of the operator influences the occurrence of short stops. If the operator chooses to control one or more components manually, the flow of materials depends a lot on the operator, which implies that there might be a difference in performance between the different operators and/or between the different crews. Section 4.1 already proved that this difference does exist in reality: the blue crew is constantly performing worse than the green crew with regard to short stops. In the current situation, there are no SOPs documented and as a result, the decision to control the line automatically or manually totally depends on the insight of the operator. Within Lean Manufacturing, this type of waste is called 'Mura': A lack of consistency in a production process because activities are not properly documented, with the result that different people at different times perform a task differently, which means that the output of the production process is not surprisingly different as well (see also Section 3.1).

4.5 Chapter conclusion

The purpose of this chapter was to answer the following research question:

"What causes the short stops?"

Answering the two sub-questions below gives answer to the research question of this chapter:

a. Which factors influence the occurrence of short stops?

This chapter showed that there are two factors influencing the occurrence of short stops. The first is the crew that is working. If the blue crew is working, the number of short stops per kilometer output is on average higher than when the green crew works. The other factor that has a significant impact on the number of short stops is the board length. When the line is processing short boards, there occur much more short stops than when long boards are being processed.

b. What are the underlying causes for these factors?

The difference between the two crews is caused by a difference in work method, and the used method depends in the current situation on the insight of the crew members because there are no SOPs documented. Next, the differences between the board lengths exists because when processing short boards, the infeed is idling more often. If the infeed is idling, it means that the second separator does not deliver enough boards to keep the planing machine busy. There are a few reasons why the second separator cannot keep up with the speed of the planing machine:

- The buffer in front of this separator is often not large enough, which results in an empty pocket;
- The top speed of the separator is only 72 cycles/min while the manufacturer promised that it would be 80 cycles/min;
- Even if the top speed was 80 cycles/min, some combinations of board length and planing speed still would not be possible for the separator.

5

Solution generation

Chapter 4 executed the first step of the Five Focusing Steps from the Theory of Constraints by identifying the second separator as the constraint of the system. This chapter carries out steps 2, 3 & 4, which answer together the last research question:

"What is the best improvement strategy for Phoenix?"

This chapter starts with a recall of the Drum-Buffer-Rope method in Section 5.1, because the possible solutions are largely based on this theory. Afterwards, Section 5.2 executes step 2 of the Five Focusing Steps by deciding how to make the most use of the bottleneck, with as low costs as possible, in order to make the most of what is available. Next, Section 5.3 is about step 3, and here we review all other activities in the process to see if they truly support the needs of the constraint. Section 5.4 executes step 4 and discusses what further actions can be taken to eliminate the second separator from being the constraint if this constraint still exists after implementing steps 2 and 3. These actions could be significant changes, and capital investment may be required. In the end, we summarize this chapter and draw our conclusions in Section 5.4.

5.1 Drum-Buffer-Rope method

A production line consists of multiple activities, which should all work synchronized for a constant material flow. The production line should contain strategic buffers to avoid that if one of the activities temporarily slows down, the whole production line slows down. This principle is called the Drum-Buffer-Rope method, which is part of the Theory of Constraints and explained in Chapter 3. The Drum-Buffer-Rope method (Figure 14) compares a production process with a chain, where each resource and function are linked. This way, the whole production process is as strong as the weakest link, also called the constraint. In this method, the constraint is called the drum and this drum determines the pace of the whole production process. Adding buffers in front and behind the drum to compensate for process variation makes this theory very stable and flexible. A buffer in front of the drum can compensate for variation earlier in the process and therefore keep the drum running at its maximum speed, while a buffer behind the drum ensures that the drum can always keep producing, even if (one of) the processes behind the drum have a failure/breakdown. The drum of the cutting and planing line is the second separator, because the number of boards this separator transports per minute determines how many boards the rest of the line can process per minute. So in order to improve the production process, the weakest link, the drum, should be optimized.

5.2 Exploit

This step is about maximizing the productivity at the constraint, which requires strategic buffering at the constraint to protect the performance of the system (Mohammadi & Eneyo, 2012). The number of boards that the separator transports per minute determines the speed of the rest of the process, which means that the separator should be fully utilized in order to achieve the maximum productivity. According to the Drum-Buffer-Rope method, this is only possible if the drum always has material to work with. We can apply this theory to our case in three possible ways:

1. Filling the pockets of separator 2 with multiple boards;
2. Eliminating empty pockets on separator 2;
3. Increasing the speed of separator 2.

5.2.1 Filling the pockets of separator 2 with multiple boards

This solution involves eliminating an activity in the cutting and planing process by not separating the boards anymore. So, instead of using the single feed unit to release one board at a time, which is the case in the current situation, boards can go immediately on the separator and no buffer needs to be formed. This way, every pocket of the separator can be filled with multiple boards, and the separator basically acts like a normal chain conveyor whose only function is transporting boards from A to B. When we look at this option from the Drum-Buffer-Rope point of view, we can say that this option increases the speed of the drum in such a way that the second separator is not the drum anymore. However, this option has a major limitation. If we do not separate the boards anymore, we can also no longer turn the boards or remove the broken boards. The purpose of turning is making sure that for example discolored sides or sides with a lot of wane are facing down, after which all further production steps can be rationalized and optimized (Kallfass-Online, n.d.). According to one of the operators, this operation is only useful if the end product is furniture for example, where the quality of boards is important, but not if the purpose of the boards is to produce pallets and the most important thing is the number of boards the cutting and planing line processes per minute. So, not being able to turn the boards anymore would not be a problem. The sorting system however is an essential function of the line, which cannot be missed. This makes that this option is practically impossible to implement.

5.2.2 Eliminating empty pockets on separator 2

Chapter 4 already mentioned that one of the biggest reasons why the separator cannot keep up with the speed of the planing machine is because there are many empty pockets on the separator, which happens when the buffer in front of the single feed unit is too small to release a board. According to the Drum-Buffer-Rope method, the length of this buffer is determined by the length of the rope, and the rope is a signal or information from the buffer to the activity prior to the drum. Figure 30 shows the location of our drum, buffer, and rope. In this figure, the direction of the wood is from right to left.

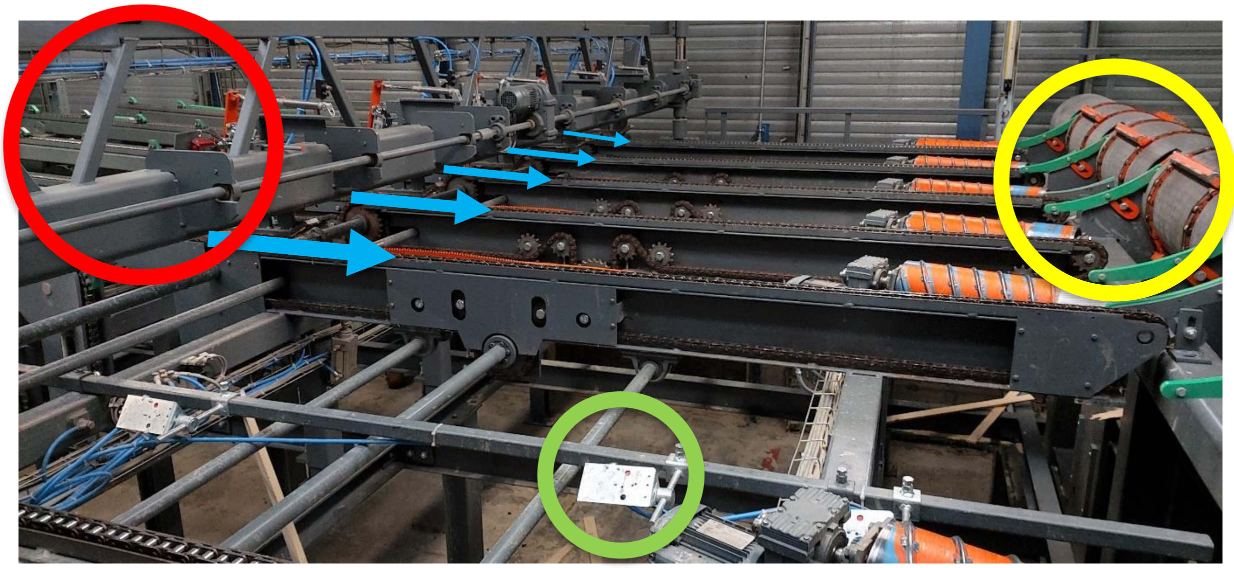


Figure 30: The drum, buffer and rope in our situation

The red circle indicates the second separator, our drum. Whether the full potential of this drum is used, depends on the length of the buffer. This buffer is located on the left side of the chain conveyors in Figure 30 (blue arrows). The length of this buffer is determined by the sensor within the green circle, which is the rope of our system. If there are boards above the sensor, it means that the buffer is full. As soon as there are no boards above the sensor anymore, the sensor gives a sign to the first separator (yellow circle) which then supplies the buffer with new boards. The buffer is on the same chain conveyor that also supplies the buffer with new boards, so obviously there is almost no difference in speed between the consumption of boards by the single feed unit and the supply of boards by the first separator. This way, there exists a gap between the buffer and the new boards that arrive at the buffer, and before the new boards arrive at the end of the buffer, the buffer is often already completely consumed by the single feed unit and is waiting for new boards, with empty pockets as a consequence. To decrease this gap, the first separator should sooner get a signal to deliver new boards. Or, to speak in terms of the Drum-Buffer-Rope method, the rope should be made longer. Making the rope longer increases the buffer length, which decreases the gap between the buffer and newly supplied boards. This decreases the chances that the buffer is entirely consumed before the new boards arrive at the buffer, which results in less empty pockets on the separator. To make the rope longer, the sensor should be placed more to the right in Figure 30. Figure 30 shows that there is still a lot of space left on the rail, so the sensor can be placed much more to the right.

However, Figure 29 shows that for the shortest boards and the highest planing speed the second separator is required to deliver 83 boards/min, and that the maximum speed of the second separator is 72 cycles/min in the current situation. This means that when every pocket is filled with a board, the separator still does not deliver enough boards/min to keep up with the planing machine. Section 5.2.3 discusses the solution for this problem.

5.2.3 Increasing the speed of separator 2

Figure 29 shows that the maximum speed of the second separator is 72 cycles/min, while this should be 80 cycles/min as promised by Kallfass. Figure 29 also contains a red area, which represents separator speeds higher than 80 cycles/min. To increase the maximum speed of the separator, Kallfass can upgrade the software of the separator by programming a new speed level and importing this into the current program of the separator. After the download, the operators can select the new higher speed level, and the second separator is able to reach 83-84 cycles/min. Increasing the speed of the second separator combined with making the rope between the two separators longer will color the yellow, blue and red areas in Figure 29 green. This means that theoretically, it will not occur anymore that the second separator cannot keep up with the speed of the planing machine.

5.3 Subordinate

The third step of the Five Focusing Steps is to subordinate everything to the decision made in the previous step (Pacheco et al., 2018). Since the second separator can process more boards/min after the Exploit phase, it is important that the other processes of the cutting and planing line are aligned with this increased separator speed. The separator, our constraint, should never be starved for new boards, and it should always have the possibility of giving boards to the next activity of the cutting and planing line. This can be achieved by maintaining reasonable buffers in front of and after the constraint. Next, established policies can reduce productivity at the constraint and must therefore also be aligned in order to achieve maximum performance. This gives us the following options for enabling the constraint to maximize its potential:

1. Subordinating the other activities of the line;
2. Adapting the purchasing policy.

5.3.1 Subordinating the other activities of the line

Planing machine

The first activity after the second separator is the planing machine. If the performance of the second separator increases after the Exploit phase, there is no need to adapt the planing machine for optimally utilizing the constraint. It is even the other way around: we want to increase the performance of the constraint because the planing machine is often not working at its maximum capacity. In front of the infeed, the part that feeds the boards to the planing machine, there is in the current situation already a few meters space available for making a buffer. So even if the planing machine is idling because a process after the planing machine has a short breakdown, the second separator can keep producing for a while to fill the buffer.

First separator

When the second separator processes more boards per minute, the first separator should deliver more boards per minute as well. In the current situation, the first separator never works at full speed, but to see if the maximum speed is high enough to keep up with the target speed we have in mind for the second separator, we counted the number of cycles the first separator processes when operating at its maximum speed. It turns out that the first separator can process 106 cycles/min, and every cycle (or pocket) can even be filled with multiple boards, depending on the board width (see Figure 6). So, the first separator does not require any technical changes when we increase the speed of the second separator because it is still possible to select a higher speed level than the current speed level.

De-stacker

The counting results in Section 4.3.1 (Figure 28) indicate that a lack of supply from the first separator is the event that causes the most short stops after the constraint itself. This means that sometimes the constraint is not utilized because there are no boards to be processed. So, this is already the case in the current situation, and we expect this event will even occur more often when the speed of the second separator increases. A lack of supply from the first separator happens when the package of wood on the de-stacker is empty. When that is the case, the de-stacker is lowering again, and pivots back to its normal position. Then, a chain conveyor puts a new package of wood on the de-stacker, the de-stackers pivots again by approximately 45 degrees, and lifts the package. Now, the new package of wood is ready to be de-stacked. All these actions can take quite some time. If the buffer after the de-stacker is totally emptied in that time, the rest of the line has no wood to process anymore, which can result in a short stop. This happens mostly when the line is processing short boards, because the planing machine needs much more boards per minute when processing short boards. The solution for this problem can be pretty straightforward. A sensor (Figure 31) measures how much boards are left in front of the first separator. If this buffer is empty, the de-stacker releases more boards from the package of wood. This buffer should be large enough to feed the first separator as long as picking up a new package takes for the de-stacker.

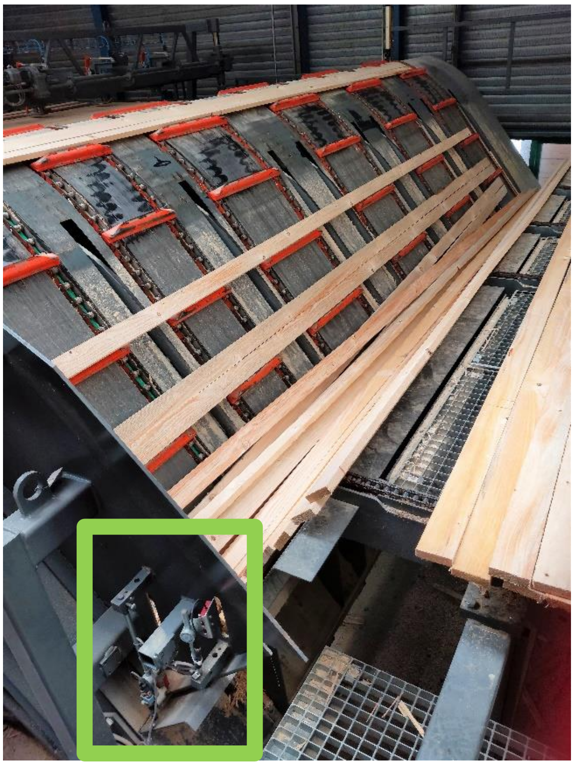


Figure 31: Sensor on separator 1

Figure 32: Sensor on separator 1 zoomed in

Figure 32 shows that the sensor is now in the lowest possible position. Moving this sensor further up ensures that the sensor gives sooner a signal to the de-stacker to release more boards. This way, the buffer in front of separator 1 is made larger, which gives the de-stacker more time for picking up a new package of wood. This way, we do not waste any of the constraints scarce capacity. However, it has one disadvantage if the buffer is always larger: it is then more difficult for the first separator to form a material film. If there are many boards in the buffer, the chances increase that a pocket picks up too many boards with the result that some boards fall back in the buffer, but that they do not fall back in the right position which makes it impossible for a next pocket to pick those boards up again. So, the best solution for subordinating the de-stacker is not to increase the buffer permanently by moving the sensor, but instead it is better if the operators pay attention when the package of wood on the de-stacker is almost empty, and when that is the case they should manually lift the de-stacker a bit more, so that there is only a bigger buffer when the de-stacker is almost empty. As we said before, this event mostly occurs when processing short boards, so the operators only need to lift the de-stacker manually when processing short boards. This way, it never happens that the constraint is not utilized because of a lack of supply from the first separator, and the changes of the mess we described before are kept to a minimum.

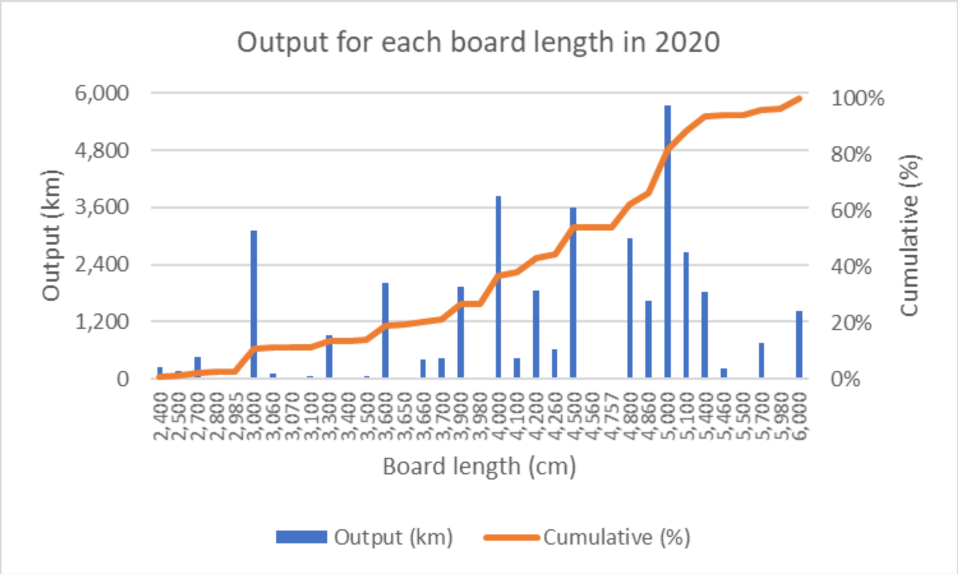
This is an practical example of a situation that depends on the insight of the operator. If the operator sees it coming that the de-stacker gets empty, he can choose to lift the de-stacker manually in order to form temporarily a larger buffer in front of the first separator. Some operators already act this way, which can (partially) declare the differences between the crews as mentioned in Section 4.1 and in Section 4.4.

5.3.2 Adapting the purchasing policy

Output

The make the circumstances for the constraint as good as possible, the company can also adapt its purchasing policy. Since long boards cause less short stops than long boards, the number of short stops can be decreased when the company only buys boards above a certain length. According to the Head Business Office of Phoenix, the price per meter is not higher for long boards than it is for short boards, so we do not have to take price differences into account. Right now, purchasing happens based on the availability of the market, so the board lengths that are available the most are purchased the most as well. To see if it is worth the effort to look actively for long boards, even if they are harder to find, we calculate how much money the company can save due to the elimination of short stops when only buying boards above a certain length.

* Figure 33 shows how much of each board length was used in 2020, so this figure represents the availability of each board length on the market as well. Chapter 4 already showed that the number of short stops that occur on average for each board length (Figure 20), so based on Figure 20 and * Figure 33, we can predict for each board length the number of short stops per year (Table 18 in Appendix 8.2). Based on these predictions, we calculate in Table 13 the expected number of short stops in a year if the company only buys boards above a certain length.



** Figure 33: Output in 2020*

Table explanation

The first column of Table 13 gives the board length, the second column how many boards longer than or equal to the length in the first column were processed on the cutting and planing line in 2020, and the third column the number of short stops that occurred in 2020 when processing boards longer than or equal to the length in the first column. Based on the second and the third column, we calculate in column four the number of short stops that occur on average when processing boards longer than or equal to the length in the first column. For example, in 2020 the cutting and planing line processed 23,400* km of boards longer than or equal to 4,200 cm, and during this time 11,241* short stops occurred, which averages 0.48 short stops per kilometer output. The fifth column gives the number of short stops that would hypothetically occur yearly when only processing boards longer than or equal to the length in the first column. For example, we said that 0.48 short stops per kilometer occur on average if we process boards longer than or equal to 4,200 cm. If all the boards we process in a year (37,751* km) are longer than or equal to this length, we would only have 37,751* x 0.48 = 18,135* short stops per year, which is 5,220* short stops per year less than the old situation. The sixth column shows these differences for each board length. Given that a short stop lasted on average 43 seconds in 2020, column 7 shows how much time can be saved if we only buy boards longer than or equal to the length in the first column.

≥ Length (cm)	* Output (km)	* Short stops (old)	Ss/km	* Short stops (new)	* Difference new/old	* Time saved (hours)
2,400	37,751	23,356	0.62	23,356	0	0
2,700	37,333	22,585	0.60	22,838	518	6
3,000	36,807	21,808	0.59	22,368	988	12
3,300	33,510	17,960	0.54	20,234	3,122	38
3,600	32,526	17,060	0.52	19,800	3,555	43
3,900	29,644	14,951	0.50	19,039	4,316	52
4,200	23,400	11,241	0.48	18,135	5,220	63
4,500	20,913	9,910	0.47	17,889	5,467	66
4,800	17,271	8,114	0.47	17,737	5,619	68

5,100	6,921	3,231	0.47	17,624	5,732	69
5,400	4,266	1,982	0.46	17,535	5,821	70
5,700	2,196	1,005	0.46	17,276	6,080	73
6,000	1,427	645	0.45	17,070	6,285	76

Table 13: Expected yearly short stops

Planing speed improvement

Chapter 1 already mentioned that short stops are stops between 20 and 45 seconds, and that stops shorter than 20 seconds are seen as a reduction in speed. Of course, the planing machine is sometimes idling less than 20 seconds as well. To give the company a better view on the impact of only buying boards longer than a certain length, we also take the speed reduction due to stops shorter than 20 seconds into account. Figure 34 shows the average planing speed for each board length. This figure shows that in practice, the maximum planing speed that is achieved in practice is 188 m/min, and that this maximum speed is not achieved for boards shorter than approximately 4,500 cm. There are two possible explanations why the average speed is lower for short boards:

1. The operators do not put the planing machine in the highest speed level, because they know that for short boards the second separator cannot keep up with a higher planing speed anyway;
2. The planing machine is idling less than 20 seconds, which is not registered as a short stop but as normal production time, but since no boards are processed in this production time the average speed decreases.

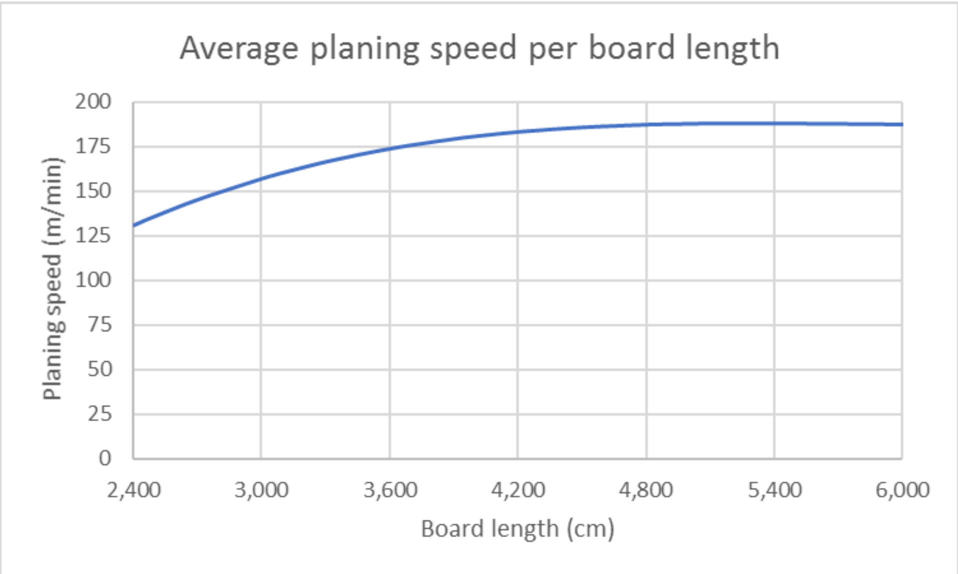


Figure 34: Average planing speed for each board length

Based on the output per board length (* Figure 33) and the planing speed per board length (Figure 34), we calculate how much time was spent on each board length in 2020 (see Table 19 in appendix 8.2). Based on Table 19 we construct Table 14 which basically works the same as Table 13.

≥ Length (cm)	* Output (m)	* Old production time (min)	Speed (m/min)	* New production time (min)	* Time saved (hours)
2,400	37,749,811	210,445	179	210,445	0
2,700	37,331,361	207,296	180	209,619	14

3,000	36,805,357	203,680	181	208,906	26
3,300	33,508,228	182,648	183	205,768	78
3,600	32,523,578	176,730	184	205,128	89
3,900	29,642,506	160,157	185	203,961	108
4,200	23,398,993	125,458	187	202,402	134
4,500	20,911,510	111,856	187	201,924	142
4,800	17,269,596	92,203	187	201,548	148
5,100	6,919,327	36,879	188	201,203	154
5,400	4,264,024	22,712	188	201,073	156
5,700	2,194,849	11,677	188	200,835	160
6,000	1,426,606	7,586	188	200,738	162

Table 14: Expected yearly production times

Cost savings

Table 14 makes clear that when buying only long boards, the increased planing speed saves even more time than the reduced number of short stops. Combining Table 13 and Table 14, we know how much time the company can save when they only buy wood above a certain length. To express these time savings into saved money, we asked the controller of the company for the hourly rates of the cutting and planing line. Table 15 shows these rates, which we divided into fixed- and variable costs. Because these costs are considered to be confidential by the company, we multiplied them by a factor Y. The reason why we choose to use a factor Y here instead of the factor X we used before, is because using two different multiplication factors enables us to show the real total costs savings (Figure 35), without the possibility that it could be traced back to confidential information. The costs that we consider as variable in Table 15 are only manhours, because if the cutting and planing line works less hours per year, these manhours can be used in another department of Phoenix, which means that the company can fill their demand for workers with their own personnel, and does not have to hire temporary workers during busy times. The fixed costs are all certain amounts per year that do not decrease when we produce less hours per year.

Fixed costs	* Amount	Variable costs	* Amount
Gas	€ 1.19	Business office	€ 14.16
Electricity	€ 20.74	Technical service	€ 6.55
Housing costs	€ 8.57	Production managers	€ 2.89
Machine depreciation	€ 71.21	Two operators	€ 79.77
Forklifts	€ 18.66		
Maintenance costs	€ 8.89		
Tool sharpening costs	€ 12.70		
Other operating costs	€ 3.53		
Total	**€ 145.50**	**Total**	**€ 103.36**

Table 15: Hourly rates for the cutting and planing line

If we need less production time for the same output, we save the variable costs of these hours. Based on Tables 13, 14, and 15, we can calculate the expected savings if the company only buys wood above a certain length. The results are visible in Figure 35, where the y-axis indicates the cost savings if the company only buys wood larger than or equal to the board length on the x-axis. The blue line represents the savings when the number of short stops decreases, the yellow line shows how much money the company can save due to an increased planing speed, and the green line is the sum of these two. Figure 35 is based on real data, so not on the anonymized figures of Tables 13, 14, and 15.

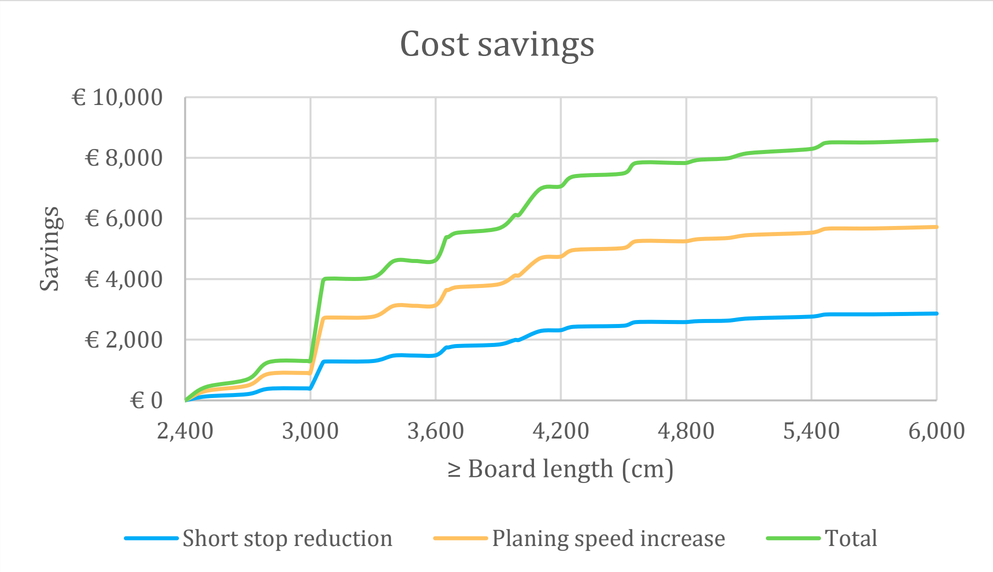


Figure 35: Cost savings when adapting the purchasing policy

What is remarkable about Figure 35 is that the costs savings rapidly increase if the company does not buy boards shorter than 3,000 cm anymore. The reason for this is that in the current situation, a relatively large portion of all the boards is 3,000 cm long (see * Figure 33), so avoiding this board length has a huge impact on the total costs. Next, we notice that for longer boards, the impact on the cost savings decreases. To illustrate this, it makes a huge difference if Phoenix only buys boards longer than 3,000 cm or if they only buy boards longer than 4,000 cm, while the difference between only buying boards longer than 5,000 cm or only 6,000 cm boards is relatively negligible. This makes sense, because we showed earlier that both the number of short stops and the planing speed depend largely on the used board length.

Waste

To see if buying only long boards saves money somewhere else we investigate how much waste is caused by the different board lengths. The cross-cut saws of the cutting and planing line cut the boards to the desired length. Most of the times, not the whole board is used because the board length is not an exact multiple of the desired length. If that is the case, a small part of the board is wasted. Table 16 shows for each board length that is ever processed on the cutting and planing line since its installation two years ago what share of the board is wasted because of the aforementioned reason, and Figure 36 represents these data graphically.

Board length	* Output (m^3)	* Waste (m^3)	Waste (%)	Board length	* Output (m^3)	* Waste (m^3)	Waste (%)
2,200	74	0	0.00%	**3,700**	1,721	58	3.42%
2,285	5	0	0.23%	**3,900**	6,895	482	6.99%
2,300	12	0	0.87%	**3,980**	184	14	7.95%
2,400	705	27	3.85%	**3,985**	126	12	10.49%

2,500	845	37	4.34%	**4,000**	18,474	406	2.20%
2,630	39	0	0.00%	**4,100**	1,765	44	2.55%
2,700	1,538	145	9.46%	**4,200**	7,120	351	4.94%
2,800	110	2	0.84%	**4,260**	2,923	69	2.34%
2,985	46	4	8.08%	**4,480**	35	0	0.00%
3,000	13,605	521	3.83%	**4,500**	16,071	422	2.63%
3,060	1,117	25	2.23%	**4,800**	11,202	328	2.93%
3,070	55	2	2.28%	**4,860**	6,071	101	1.66%
3,100	269	9	3.38%	**5,000**	28,895	1,023	3.54%
3,300	3,618	168	4.67%	**5,060**	80	0	0.20%
3,360	30	0	0.00%	**5,100**	9,975	489	4.90%
3,400	5	0	8.68%	**5,400**	8,690	280	3.22%
3,420	30	0	0.00%	**5,460**	535	11	2.12%
3,450	57	0	0.87%	**5,490**	12	0	1.64%
3,500	206	11	5.01%	**5,500**	5	0	5.45%
3,525	53	0	0.00%	**5,700**	2,949	78	2.66%
3,600	10,564	278	2.64%	**5,980**	39	2	3.01%
3,650	37	0	1.92%	**6,000**	6,944	140	2.01%
3,660	2,574	55	2.10%				

Table 16: Average waste for each board length

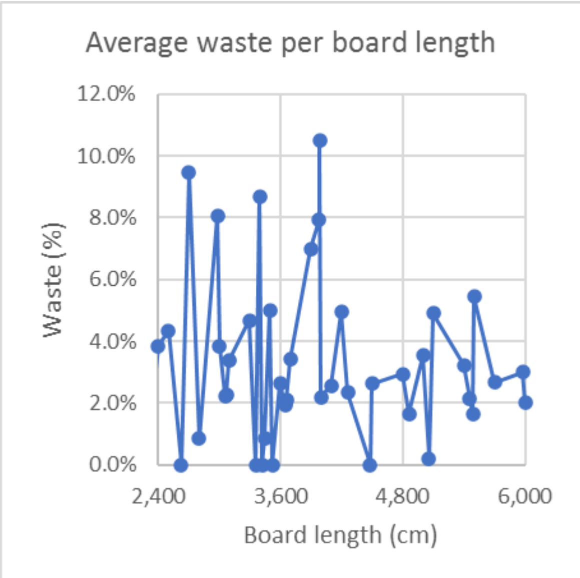


Figure 36: Average waste for each board length

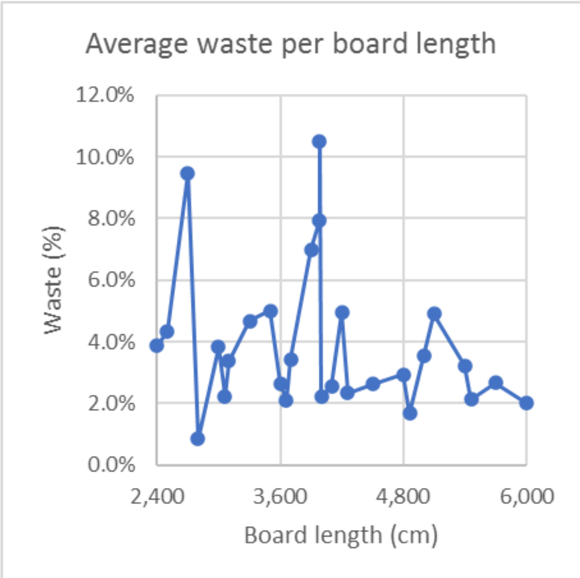


Figure 37: Waste vs. board length without outliers

From Figure 36, it seems that short boards have a higher waste percentage than longer boards. However, if we remove the board lengths that are almost never processed in the past two years (less than 90 m^3 output), it turns out that in practice the amount of waste does not depend very much on the board length (Figure 37). There are only a few peaks in Figure 37: 2,700 cm, 3,900 cm, 3,980 cm, and 3,985 cm. If we do not these peaks into consideration, the graph is evenly distributed for all board lengths. So, buying only long boards does unfortunately not have the additional advantage of less waste.

Conclusion

If the company only buys the longest boards, the total time savings can be €8,581, which is a considerable amount. However, this is easier said than done because those long boards are not always available on the market. At the moment of writing, wood is even so scarce that the company buys whatever they can get their hands on, which means that they do not have the luxury of choosing between boards. Next to that, adapting the purchasing policy is avoiding the problem rather than solving it. So, this section can give insight to the company about the impact the problem has in terms of money, but adapting the purchasing policy cannot be considered as the solution for the problem.

5.4 Elevate

According to the Theory of Constraints, if steps 2 & 3 of the Five Focusing Steps have not been successful, it is time to consider further actions for eliminating the constraint. In step 4 of the Five Focusing Steps, a larger investment might be required. Here, we discuss two options that will most certainly eliminate the constraint:

1. Inserting two chain conveyors;
2. Evaluating the whole line.

5.4.1 Two chain conveyors

Sensor

Section 5.2.3 mentioned the option of increasing the maximum speed of the second separator. However, increasing the maximum performance of the separator does not make a lot of sense if the extra cycles that become available cannot be filled with a board. Section 5.2.2 mentioned that the buffer in front of the second separator is on the same chain conveyor that also supplies the buffer with new boards, which means that there is almost no difference in speed between the consumption of boards by the single feed unit and the supply of boards by the first separator, with empty pockets as a consequence. To solve this problem, Section 5.2.2 discussed the possibility of adapting the rope in order to make the buffer longer, with the ultimate goal of eliminating empty pockets on the second separator. However, there might be a chance that the sensor in Figure 30 cannot be placed much more to the right, because placing the sensor too close to the first separator causes that the first separator 'throws' the boards on top of the buffer instead of behind the buffer. Practice will show what the optimal location of the sensor is, but we expect that this optimal location will only increase the buffer with a few boards, and it is very unlikely that a few extra boards in the buffer eliminate all empty pockets on the second separator.

Wood supply

If the creation of a buffer and the supply of new boards to the buffer happens on two different chain conveyors, the wood supply can be controlled much better, because this variant can feed and accelerate independently from one another. The first chain conveyor can accelerate the boards and bring them to the buffer quickly, while the second chain conveyor, which contains the buffer, has the purpose of feeding the boards to the single feed unit. With this system, there is no gap anymore between the buffer and the newly supplied boards, with no empty pockets as a consequence. So, a system with two chain conveyors sounds like an ideal solution: this way, the sorting- and turning systems are retained, while it does not reduce the performance of the cutting and planing line. This system, however, needs more space between the two separators: for installing this system we must have between 1.5 and 2 meters available, according to Kallfass. As visible in Figure 30, the current system is barely 2 meters long so adapting the current system to one with two chain conveyors can be problematic.

5.4.2 Evaluate the whole line

Sorting system
Section 5.4.1 finished with the suggestion that the two separators might be too close to each other, which limits a smooth process flow. So, if it is not possible to implement two chain conveyors between the separators, as discussed in Section 5.4.1, the last possibility we have is to evaluate all the processes between the de-stacker and the planing machine. When doing so, we might even say that the whole cutting and planing line is too complicated for what it is actually supposed to do. Between de-stacking the boards and feeding them to the planing machine, there does not happen much more than actually de-stacking and feeding the boards. The whole purpose of the second separator is enabling the turning- and sorting systems to do their job. These systems, however, are not required to have in this form. As explained in Section 5.1.2, the turning system is not used by the operators, so missing this system is not a big problem. Next to that, sorting the wood also does not require the wood to be separated first if another sorting system was installed, similar to how the boards are sorted on another cutting line in the sawing department of Phoenix. This sorting system is basically a small chain conveyor, which the operator can shift back with simply pressing a button, which results in a 'gap' in the cutting line. When the operator presses the button at the right moment and closes the 'gap' again at the right moment, the defect board falls through the 'gap' in a disposal container under the chain conveyors. If the button is not pressed and released at the right moment, the wrong board/multiple boards might be disposed, so it might take some practice before the operators master this system.

Muda
This alternative sorting system does not slow down the flow of materials, which makes that the activity as currently performed by the second separator is not necessarily required in the cutting and planing process. Activities in a process that do not add value to the operation or the customer are a type of waste called 'Muda' in Lean Manufacturing (see Section 3.1), so the Lean way of working would be to remove the second separator. If this separator is removed, the boards could be transported directly from the first separator to the infeed, practically with unlimited speed. As a result, there would never be a problem with an idling planing machine.

Cost-Benefit
Table 13 shows that in 2020, there occurred approximately 23,356* short stops with 37,751* kilometer output. If there did not occur any short stops because of an idling planing machine, every board length would perform the same as the longest board length, which is approximately 0.45 short stops/kilometer output (Table 18). We already calculated in Section 5.3.2 that if the cutting and planing line only processes boards that are 6,000 cm long, it would yearly save 238* hours, which equals €8,581. This means that without a second separator, the yearly cost savings would also be €8,581. Surely, a drastic change like removing the second separator would require a major investment, which is even extra painful because barely two years ago, installing the second separator cost over €200,000. However, if removing this piece of equipment saves yearly the aforementioned sum of money for the rest of the cutting and planing line's lifetime, it is definitely worth considering this option.

5.5 Chapter conclusion

In the introduction of this chapter, answering the following research question was mentioned as the goal for this research:

"What is the best improvement strategy for Phoenix?"

This research question is answered by finding answers to these two sub-questions:

a. How can Phoenix solve the previously found root causes, and hence eliminate most of the short stops?

First, the company should exploit the constraint, which means making the most of what is available. To do this, they should upgrade the software of the second separator as Kallfass offered, and adapt the rope of the system by replacing the sensor that is indicated in Figure 30. Next, it is important to subordinate everything else, which involves selecting a higher speed level for the first separator, so it can always keep up with the speed of the second separator. To avoid an empty buffer after the de-stacker while the de-stacker is picking up a new package of wood, the operators should release manually the last layers of each package of wood when processing short boards, to make sure that there is always enough wood to process while the de-stacker is changing packages. If these two steps did not achieve the desired result, the improvement strategy is expanded with step 4 of the Five Focusing Steps, where some more drastic changes to the cutting and planing line eliminate the second separator from being the constraint.

b. Which costs and benefits are involved in this strategy?

In the first two steps of the improvement strategy (Exploit & Subordinate), no costs are involved. The cutting and planing line was installed only two years ago, so it is still under warranty and therefore updating the separator speed to the speed it is supposed to be does not cost anything. Furthermore, replacing a sensor and training the operators to apply the new work methods may cost some time, but there are no direct costs involved. Only when these two steps do not give the desired result and the company chooses to start step 4 of the Five Focusing Steps, a major investment is required. The exact amount is still unknown, which is why we advise the company in the next section to investigate the costs involved in the Elevate step. The ultimate goal of this improvement strategy is that the second separator is not the constraint anymore, and that all boards behave like the longest board, which means as yearly benefit of €8,581 as explained in Section 5.4.2.

6

Conclusion and recommendations

This last chapter provides the conclusion and discussion of the research, and gives recommendations for improvement and for further research. Section 6.1 gives the conclusion of the research, while Section 6.2 discussed the results of this research. In Section 6.3 we do our recommendations to the company.

6.1 Conclusion

Research questions

The research of this thesis assignment focused on finding ways for eliminating short stops of the cutting and planing line of Phoenix. To draw our conclusions whether we achieved our goal, we first answer the in Chapter 1 formulated research questions.

1. What is the current situation of the cutting and planing line?

We answered this question by looking at the situation of 2020. The average OEE was 53.9% in this year, and the Availability component of this OEE was 66.4%. One of the biggest availability losses in 2020 were the short stops. The total available time in this year was 3,382 hours and from this available time, 4.6% was wasted with short stops, which equals 154 hours. When we involved the output in this discussion, we saw that the number of short stops varied between 0.4 and 0.8 short stops per kilometer output in 2020, with an average value of 0.63.

2. What available literature is relevant for this research?

In this research, we used a combination of Lean Manufacturing and the Theory of Constraints. Identifying the constraint that is the root cause of most short stops is the first step of the Five Focusing Steps from the Theory of Constraints and during this step, we used various principles of Lean Manufacturing, like Gemba walks to get a better understanding of the problem itself and the current situation, an Ishikawa diagram that proposes possible causes for short stops, and the Why-Why Analysis to find the underlying reasons for the existence of the root causes. Next, we executed steps 2, 3 & 4 of the Five Focusing Steps from the Theory of Constraints to find the best improvement strategy that eliminates short stops. Within this structure, we used again some Lean Manufacturing principles, like the ‘Muda, Mura, Muri’ principle to identify causes of waste that should be reduced or eliminated.

3. What causes the short stops?

This research showed that two factors influence the occurrence of short stops. The first is the crew that is working. If the blue crew is working, the number of short stops per kilometer output is on average higher than when the green crew works. The difference between the two crews is caused by a difference in work method, and the used method depends on the insight of the crew members. The other factor that has a significant impact on the number of short stops is the board length. When the line is processing short boards, there occur much more short stops than when long boards are being processed. These differences exist because when processing short boards, the infeed is idling more often. If the infeed is idling, it means that the second separator does not deliver enough boards to keep the planing machine busy. There are a few reasons why the second separator cannot keep up with the speed of the planing machine:

- The buffer in front of this separator is often not large enough, which results in an empty pocket;
- The top speed of the separator is only 72 cycles/min while the manufacturer promised that it would be 80 cycles/min;
- Even if the top speed was 80 cycles/min, some combinations of board length and planing speed still would not be possible for the separator.

4. What would be the best improvement strategy for Phoenix?

In the first step of the improvement strategy, the company should exploit the constraint, which means making the most of what is available. To do this, they should upgrade the software of the second separator in order to increase the maximum speed of this separator, and they should increase the buffer in front of the single feed unit by replacing the sensor that is indicated with the green circle in Figure 30.

Next, it is important to subordinate everything else, which involves selecting a higher speed level for the first separator, so it can always keep up with the speed of the second separator. To avoid an empty buffer after the de-stacker while the de-stacker is picking up a new package of wood, the operators should release manually the last layers of each package of wood when processing short boards, to make sure that there is always enough wood to process while the de-stacker is changing packages.

In these first two steps of the improvement strategy, no costs are involved. The cutting and planing line was installed only two years ago, so it is still under warranty and therefore updating the separator speed to the speed it should be costs nothing. Furthermore, replacing a sensor and training the operators to apply the new work methods may cost some time, but there are no direct costs involved. Only when these two steps do not achieve the desired result, the improvement strategy is expanded with step 4 of the Five Focusing Steps.

In this step, some more drastic changes to the cutting and planing line eliminate the second separator from being the constraint. We mention two possibilities: implementing a system with two separate two chain conveyors that work independently of one another, or removing the second separator entirely. Both possibilities require a major investment. The exact amount is still unknown, which is why we advise the company in Section 6.3.2 to investigate the costs involved in the Elevate step. The ultimate goal of this improvement strategy is that the second separator is not the constraint anymore, and that all boards behave like the longest board, which means as yearly benefit of €8,581 as explained in Section 5.4.2.

Action problem
After answering the research questions, the knowledge of the literature combined with the analysis of the data ultimately solved the action problem of this research, which was formulated as follows:

"The sum of all short stops as a percentage of the available time is on average 4.6%, and we want to bring this figure back to at most 2%."

Chapter 2 mentioned that in the current situation, there occur on average 0.63 short stops per kilometer output. After implementing the improvement strategy, all boards will behave like the longest boards which means that on average, the number of short stops per kilometer will be on average 0.45 (see Table 18). This means that the number of short stops decreases by 29%. In reality, 4.6% of the available time is lost to short stops, and if this figure decreases by 29%, only 3.3% of the available time is lost to short stops. At the start, 2% was chosen as the norm so that this research had a figure to work towards. Unfortunately, this norm cannot be achieved with the proposed improvement strategy. However, due to the nature of the short stops we eliminate, we enable the planing machine to reach for all board lengths the average speed of the longest board lengths in Figure 34, which is approximately 188 m/min. Since the maximum speed of the planing machine is 200 m/min, achieving 188 m/min on average makes the Performance component of the OEE 188/200 = 94%. If we take this into account, the OEE after implementing the improvement strategy will become 63.2%, based on the average OEE of 2020. The OEE would only have been 56.0% if we met the norm of 2% without being able to increase the planing speed. Therefore, we can say that due to this side effect, this project can still be considered as a success.

6.2 Discussion

The results and validation of the results are discussed in this section. The assumptions that are made and the approach of this research have consequences for the reliability of the results and thus, the advice that is given to Phoenix. Since it is impossible to discuss all the possible unknown effects and assumptions of the research, only the most important ones are discussed. First, this research focused on the short stops of the cutting and planing line. It can be possible that the proposed solutions cause failures other than short stops, so that is something to take into account when implementing the solutions. Second, the proposed changes enable the planing machine to work at its top speed at all times, but the effect of a changed production speed on the health of the machine is not known. It is up to Phoenix to decide if changing the production speed is worth the risk of more failures. Next, the average planing- and separator speeds are calculated based on only two months of data, which can reduce the reliability of the average speed levels and hence the reliability of the final recommendations. Lastly, there was no time to implement and evaluate the proposed solutions yet. The company made an appointment with Kallfass for the near future, but unfortunately it was not possible for them to update the separator speed within the time we have available for this research and therefore, this thesis does not contain an evaluation of the improvement strategy.

6.3 Recommendations

This section provides our recommendations for Phoenix. We divided this section into two different sub-sections: Section 6.3.1 provides our recommendations on how to decrease the number of short stops on the cutting and planing line, and Section 6.3.2 discusses topics for further research.

6.3.1 Recommendations for improvement

After this thesis assignment, we have a few recommendations for improvement for Phoenix. After each recommendation, we mention the section that explains the recommendation. The recommendations are:

- Improve the speed of the second separator to 84 cycles/min (see Section 5.2.3);
- Find the optimal position for the sensor that determines the buffer length in front of the second separator (see Section 5.2.2);
- Develop and implement SOPs and ensure that they are actually used as well (See Section 5.3.1);
- Measure the impact of these measures on the OEE and on the occurrence of short stops by counting (see Section 4.3.1);
- If the desired result is not achieved after the previous step, consider starting step 4 of the Five Focusing Steps (see Section 5.4).

6.3.2 Recommendations for further research

Follow-up research

In case the improvement actions of Section 6.3.1 were not sufficient, which means that the planing machine is still idling sometimes when processing short board lengths, we recommend to consider starting step 4 of the Five Focusing Steps. Section 5.4 explain this step in detail, and it involves some drastic changes of the cutting and planing line. There are two possibilities here: implementing a system with two conveyor chains (Section 5.4.1), and removing the second separator (Section 5.4.2). Both options require a major investment, so we advise Phoenix to investigate in detail the costs and benefits that are involved with both options.

Short stops

After implementing the improvement action that we mentioned in Section 6.3.1, the skewness in Figure 20 is eliminated and the occurrence of short stops is the same for all board lengths. If that is the case, the number of short stops per kilometer output is 0.45 ss/km, or 3.3% of the total available time. When we compare that last figure with Figure 3 in Chapter 1, we see that the occurrence of short stops is then still one of the biggest losses. Section 4.3 already categorized the reasons for the occurrence of short stops (Figure 28), so a recommendation to Phoenix is to investigate the root causes of the remaining events further, in order to decrease the number of short stops further.

OEE

According to Nakajima (1988), the ideal values for a world class OEE are more than 90% for the Availability component, more than 95% for the Performance component, and more than 99.9% for the Quality component (Ngadiman, Hussin & Abdul Majid, 2013). Chapter 1 already showed that the Quality component of the cutting and planing line's OEE is 100%, so this component cannot be improved further. Next, this research showed that if the second separator can always keep up with the speed of the planing machine, the maximum speed of Figure 34 can be achieved at all times, which means that the Performance component becomes 188/200 = 94%, which is almost the target Performance for an excellent OEE. So, in order to achieve a world class OEE, the remaining Availability losses should be addressed. This is the last step of the Five Focusing Steps, because the Five Focusing Steps is a continuous improvement cycle, which means that once a constraint is resolved the next constraint should immediately be addressed. So basically, we recommend to start step 1 of the Five Focusing Steps again. In Chapter 1, we already mentioned the Availability losses that cause the most time losses (Figure 3), and the next step in improving the OEE of the cutting and planing line would be eliminating one of these losses. Therefore, my final recommendation to Phoenix is to keep improving the OEE of the cutting and planing line, because there is still a lot of unused potential.

7

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8
Appendices

8.1 OEE Time Registration on January 4, 2020

Activity:	Start time:	Duration:	Activity:	Start time:	Duration:
Changeover	06:00:00	00:00:05	**Short stop**	11:43:24	00:00:36
Production	06:00:06	00:00:40	**Short stop**	11:47:58	00:00:36
Changeover	06:00:47	00:01:43	**LEDINEK board broke in infeed**	11:48:47	00:02:06
Production	06:02:31	00:00:11	**Production**	11:50:53	00:10:06
KALLFASS other	06:02:42	00:10:17	**LEDINEK wood jam in planing machine**	12:00:59	00:01:47
Production	06:12:59	00:00:11	**Production**	12:02:46	00:00:03
KALLFASS other	06:13:11	00:02:47	**LEDINEK wood jam in planing machine**	12:02:49	00:01:33
Production	06:15:59	00:05:02	**Production**	12:04:23	00:00:02
Short stop	06:16:12	00:00:40	**Break**	12:04:25	00:31:45
Short stop	06:20:03	00:00:52	**Production**	12:36:11	00:00:50
KALLFASS de-stacker failure	06:22:34	00:05:02	**KALLFASS de-stacker failure**	12:37:01	00:01:02
Production	06:27:36	00:23:41	**Production**	12:38:04	00:14:11
Short stop	06:31:10	00:00:40	**KALLFASS rearrange wood at stacker**	12:52:15	00:02:54
Short stop	06:31:54	00:00:41	**Changeover**	12:55:09	00:04:31
Short stop	06:34:47	00:00:37	**Production**	12:59:41	00:00:04
Short stop	06:36:27	00:00:36	**KALLFASS strapper failure**	12:59:46	00:01:04
Short stop	06:53:37	00:00:39	**Production**	13:00:50	00:00:13
Short stop	06:54:21	00:00:37	**KALLFASS strapper failure**	13:01:03	00:20:32
LEDINEK wood too thick/wide	06:55:12	00:01:05	**Production**	13:21:36	00:00:37
Production	06:56:17	00:02:19	**LEDINEK wood too thick/wide**	13:22:14	00:01:15
LEDINEK wood too thick/wide	06:58:37	00:01:24	**Production**	13:23:30	00:02:09
Production	07:00:02	00:06:18	**KALLFASS board broke in planing machine**	13:25:39	00:04:01
KALLFASS board broke in saws	07:06:20	00:05:30	**Production**	13:29:40	00:00:13
Production	07:11:51	00:13:41	**KALLFASS board broke in planing machine**	13:29:54	00:02:02
Short stop	07:13:01	00:00:59	**Production**	13:31:56	00:01:04
Short stop	07:14:09	00:00:59	**KALLFASS de-stacker failure**	13:33:00	00:01:25
LEDINEK wood too thick/wide	07:27:32	00:01:05	**Production**	13:34:26	00:23:50
Production	07:28:37	00:09:36	**Short stop**	13:37:14	00:00:59
Short stop	07:33:21	00:00:35	**Short stop**	13:54:10	00:00:44

Short stop	07:36:40	00:00:59	**Production**	14:00:01	00:10:43
LEDINEK board broke in infeed	07:39:49	00:03:12	**KALLFASS stickdropper failure**	14:10:45	00:01:26
Production	07:43:02	00:05:39	**Production**	14:12:11	00:13:44
Short stop	07:43:25	00:00:36	**Short stop**	14:12:52	00:00:39
LEDINEK wood too thick/wide	07:49:18	00:01:08	**Short stop**	14:16:28	00:00:41
Production	07:50:26	00:31:40	**LEDINEK air extractor failure**	14:27:16	00:01:02
Short stop	08:01:04	00:00:39	**Production**	14:28:19	00:00:42
Short stop	08:09:21	00:00:40	**LEDINEK air extractor failure**	14:29:01	00:15:50
Short stop	08:17:45	00:00:36	**Production**	14:44:52	00:09:21
KALLFASS rearrange wood at stacker	08:24:04	00:02:22	**Short stop**	14:53:45	00:00:58
Production	08:26:26	00:00:25	**LEDINEK sensor not free**	14:55:11	00:01:08
LEDINEK board broke in infeed	08:26:52	00:02:44	**Production**	14:56:20	00:09:58
Production	08:29:37	00:02:47	**Changeover**	15:06:18	00:06:36
Short stop	08:30:07	00:00:44	**Production**	15:12:55	00:01:51
LEDINEK board broke in infeed	08:33:08	00:02:17	**Production**	15:14:47	00:06:18
Production	08:35:26	00:18:11	**Short stop**	15:16:09	00:00:39
KALLFASS de-stacker failure	08:53:37	00:01:15	**Short stop**	15:17:03	00:00:46
Production	08:54:53	00:04:18	**Short stop**	15:19:47	00:00:45
Short stop	08:59:09	00:00:44	**Short stop**	15:20:44	00:00:59
Changeover	08:59:55	00:11:26	**Short stop**	15:24:05	00:00:33
Production	09:11:22	00:00:53	**KALLFASS de-stacker failure**	15:24:50	00:03:17
Changeover	09:12:15	00:03:10	**Production**	15:28:07	00:00:04
Production	09:15:25	00:00:10	**LEDINEK sensor not free**	15:28:12	00:02:32
Break	09:15:36	00:19:14	**Production**	15:30:44	00:15:54
Production	09:34:50	00:03:26	**Changeover**	15:46:38	00:03:32
Short stop	09:35:38	00:00:45	**Production**	15:50:11	00:05:58
KALLFASS rearrange wood at stacker	09:39:02	00:01:41	**Break**	15:56:09	00:21:44
Production	09:40:44	00:00:08	**Production**	16:17:54	00:01:18
Changeover	09:40:52	00:01:13	**Changeover**	16:19:12	00:07:28
Production	09:42:06	00:01:16	**Production**	16:26:41	00:00:30
Changeover	09:43:23	00:01:10	**Short stop**	16:26:44	00:00:51
Production	09:44:34	00:05:03	**LEDINEK wood too thick/wide**	16:28:03	00:01:27
Short stop	09:49:12	00:00:32	**Production**	16:29:30	00:04:14
KALLFASS de-stacker failure	09:50:10	00:02:23	**LEDINEK sensor not free**	16:33:45	00:03:39
Production	09:52:34	00:01:45	**Production**	16:37:24	00:02:31
Short stop	09:53:29	00:00:42	**KALLFASS rearrange wood at stacker**	16:39:55	00:01:57
LEDINEK wood too thick/wide	09:55:02	00:01:01	**Production**	16:41:53	00:14:45
Production	09:56:04	00:10:51	**No production planned**	16:56:39	02:57:14
Short stop	10:03:11	00:00:53	**Production**	19:53:53	00:57:37
LEDINEK wood jam in planing machine	10:07:48	00:05:12	**KALLFASS rearrange wood at stacker**	20:51:30	00:02:13
Production	10:13:01	00:12:29	**Production**	20:53:44	00:09:56
Short stop	10:18:31	00:00:32	**KALLFASS rearrange wood at stacker**	21:03:41	00:01:29
Changeover	10:26:03	00:04:11	**Production**	21:05:10	00:06:41
Production	10:30:14	00:01:29	**KALLFASS external conveyor belt failure**	21:11:52	00:01:14

Short stop	10:31:01	00:00:57	**Production**	21:13:06	00:27:23
LEDINEK wood too thick/wide	10:32:41	00:01:47	**Break**	21:40:29	00:17:17
Production	10:34:29	00:17:23	**Production**	21:57:46	00:00:10
Short stop	10:35:45	00:00:31	**KALLFASS board broke in planing machine**	21:57:57	00:02:02
Short stop	10:39:59	00:00:42	**Production**	21:59:59	00:00:02
Short stop	10:41:01	00:00:44	**KALLFASS board broke in planing machine**	22:00:01	00:01:38
Short stop	10:42:18	00:00:42	**Production**	22:01:40	00:00:02
Short stop	10:50:14	00:00:54	**KALLFASS board broke in planing machine**	22:01:42	00:02:08
Short stop	10:52:10	00:00:56	**KALLFASS board broke in planing machine**	22:00:01	00:01:38
LEDINEK wood too thick/wide	10:56:25	00:01:03	**Production**	22:01:40	00:00:02
Production	10:57:28	00:24:01	**KALLFASS board broke in planing machine**	22:01:42	00:02:08
Short stop	11:02:56	00:00:50	**Production**	22:03:50	00:02:46
Short stop	11:05:37	00:00:51	**KALLDASS other**	22:06:37	00:02:12
Short stop	11:09:49	00:00:43	**Production**	22:08:50	00:00:02
Short stop	11:11:17	00:00:34	**LEDINEK board broke in infeed**	22:08:52	00:02:00
Short stop	11:12:17	00:00:37	**Production**	22:10:52	01:07:28
Short stop	11:17:05	00:00:35	**Short stop**	22:13:12	00:00:41
Short stop	11:20:41	00:00:45	**Short stop**	22:21:42	00:00:54
Short stop	11:23:10	00:00:40	**Short stop**	22:40:38	00:00:35
Short stop	11:27:02	00:00:51	**KALLFASS external conveyor belt failure**	23:20:32	00:01:39
Changeover	11:28:00	00:10:40	**Production**	23:22:11	00:02:13
Production	11:38:40	00:00:02	**Short stop**	23:24:22	00:00:42
LEDINEK wood too thick/wide	11:38:43	00:01:14	**Cleaning**	23:25:07	00:19:53
Production	11:39:58	00:07:36			

Table 17: All OEE activities of January 4, 2021 including timestamps

8.2 Impacts of adapting the purchasing policy

Length (cm)	* Output (km)	Ss/km	* Short stops
2,400	142	1.90	270
2,500	94	1.75	165
2,700	267	1.49	398
2,800	22	1.38	30
2,985	8	1.18	9
3,000	1,764	1.17	2,065
3,060	61	1.12	68
3,070	6	1.11	7
3,100	29	1.08	31
3,300	518	0.92	479
3,400	1	0.86	1
3,500	36	0.80	29
3,600	1,141	0.74	848
3,650	18	0.72	13
3,660	228	0.71	163
3,700	239	0.70	166
3,900	1,092	0.62	675
3,980	21	0.59	12
4,000	2,159	0.59	1,266
4,100	251	0.56	141
4,200	1,048	0.54	564
4,260	355	0.53	187
4,500	2,029	0.49	1,001
4,560	3	0.49	1
4,757	23	0.48	11
4,800	1,670	0.47	792
4,860	923	0.47	436
5,000	3,246	0.47	1,527
5,100	1,498	0.47	705
5,400	1,036	0.47	489
5,460	131	0.47	62
5,500	1	0.47	0
5,700	420	0.47	197
5,980	14	0.45	6
6,000	805	0.45	364

Table 18: Expected yearly short stops for all board lengths

Length (cm)	* Output (m)	Speed (m/min)	* Production time (hours)
2,400	141,797	131	1,082
2,500	94,288	136	695
2,700	266,844	145	1,841
2,800	22,089	149	148
2,985	7,833	156	50
3,000	1,764,114	157	11,262
3,060	61,384	159	387
3,070	5,971	159	38
3,100	28,737	160	180
3,300	518,417	166	3,122
3,400	1,051	169	6
3,500	36,061	171	211
3,600	1,140,714	173	6,580
3,650	17,703	174	102
3,660	227,842	175	1,305
3,700	239,212	175	1,364
3,900	1,091,594	179	6,104
3,980	20,935	180	116
4,000	2,159,088	180	11,975
4,100	250,908	182	1,382
4,200	1,048,085	183	5,736
4,260	355,327	183	1,938
4,500	2,029,091	185	10,951
4,560	3,010	186	16
4,757	22,629	187	121
4,800	1,670,198	187	8,942
4,860	923,181	187	4,938
5,000	3,246,135	187	17,333
5,100	1,498,094	187	7,993
5,400	1,035,725	187	5,524
5,460	130,527	188	696
5,500	1,155	188	6
5,700	419,543	188	2,234
5,980	13,892	188	74
6,000	804,876	188	4,280

Table 19: Expected yearly production times for all board lengths

8.3 Confidentiality issues

This section is left blank due to confidentiality issues.