Internship report

Effectiveness improvement of Nelson Pine MDF sawing machine

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GoldenEdge Medium Density Fibreboard ®

Preface

What started as a ”Production Nelson” Google search when looking for an internship, resulted in the fulfillment of the internship that I have done at Nelson Pine Industries Ltd, in Nelson, New Zealand. The internship took place from the 15th of August to the 18th of November. Before you, lies the corresponding report, ”Effectiveness improvement of Nelson Pine MDF sawing machine”.

The internship was a great experience in which I could finally apply the knowledge that I learned in the past five years, and especially the last year. My master course Mechanical Engineering, with the specialization ”Design, Production & Management” has formed a great basis for the activities that I have done at Nelson Pine. I have especially used knowledge from the courses ”Simulation”, ”Lean Six Sigma Green Belt” and ”Discrete Optimization of Business Processes”.

I want to thank Wieteke de Kogel, for assessing the internship, but especially also for stimulating students to do the internship abroad. Next to that, I want to thank everybody at Nelson Pine for their hospitality and willingness to help. I felt welcome from the first day. John, thank you for your positive attitude all the time. Corey, thank you for all the time you spent explaining me things at the B-saw. Ben, thank you for your gratitude in doing the projects I have done. Steve, thank you for having the confidence in accepting me as an intern. Last, but absolutely not least, thank you, Caleb, for everything you have done in helping me: from lending me a bike, to introducing me to everybody at Nelson Pine, to eating curries with my Indian roommates.

Tom Otjens

Nelson, November 18, 2016

Abstract

English

This research looks at the improvement of the capacity of one of the three MDF sawing machines at Nelson Pine Industries Ltd, to reduce overtime of the sawing machines. The overall equipment effectiveness is used as a framework for improvements. By doing a Pareto analysis on the downtime causes of one year, the top ten downtime causes are found. These downtime causes are discussed with Nelson Pine. One of the causes is solved during this research, which should reduce the downtime by at least 6%. An additional result is that the solution should increase the quality of the MDF. To increase the speed of the sawing machine, a simulation study is done. By implementing the results of the simulation study, the throughput should be increased by almost 10%. Since this is amplified by a higher uptime, this research leads to a direct increase in overall equipment effectiveness of the sawing machine of about 16%. Next to that, by implementing a system which automatically records the downtime and the related downtime causes, this research should facilitate with a culture of continuous improvements.

Nederlands

Dit onderzoek kijkt naar de verbetering van de capaciteit van één van de MDF zaagmachines bij Nelson Pine Industries Ltd, met als doel om overuren te verminderen van de zaagmachines. De ”overall equipment effectiveness” wordt gebruikt als leidraad voor verbeteringen. Door de uitvoering van een Pareto analyse op de oorzaken van machine uitval van het afgelopen jaar, zijn de tien belangrijkste oorzaken van machine uitval gevonden. Deze oorzaken zijn besproken met Nelson Pine. Eén van deze tien oorzaken is tijdens deze stage opgelost. Dit zou voor een vermindering van 6% van de machine uitval moeten zorgen. Een bijkomend resultaat is dat het de kwaliteit van het MDF zal verbeteren. Een simulatie studie is gedaan om de snelheid van de zaagmachines te verhogen. De snelheid wordt met bijna 10% verhoogd door de resultaten van de simulatie studie te implementeren. Omdat deze verhoging wordt versterkt door een verlaging van de machine uitval, leidt dit onderzoek tot een overall equipment effectiveness verhoging van ongeveer 16%. Daarnaast, door de implementatie van een systeem dat automatisch de redenen van machine uitval registreert, helpt dit onderzoek met het inbrengen van een cultuur van continue verbeteringen.

Contents

Chapter 1

Introduction

Nelson Pine Industries Limited is the producer of GoldenEgde Medium Density Fibreboard (MDF). MDF is mainly applied for indoor use, such as furniture. It is made by pressing wood fibres, wax and a resin together under high temperature and pressure.

Before starting the internship, the goal was to do improvements at the sanding and sawing machines. See 2 Background for more information about Nelson Pine and the production steps of MDF. Once arrived, it was determined in more detail what the goal would be. Since the three sawing machines at Nelson Pine currently regularly must do overtime in the weekends, it is decided to research how the capacity of the sawing machines can be increased.

The overall equipment effectiveness (OEE) is used in this report as a framework of the capacity, to illustrate what kind of improvements are made. See *Figure 1.1* for an illustration of the OEE.

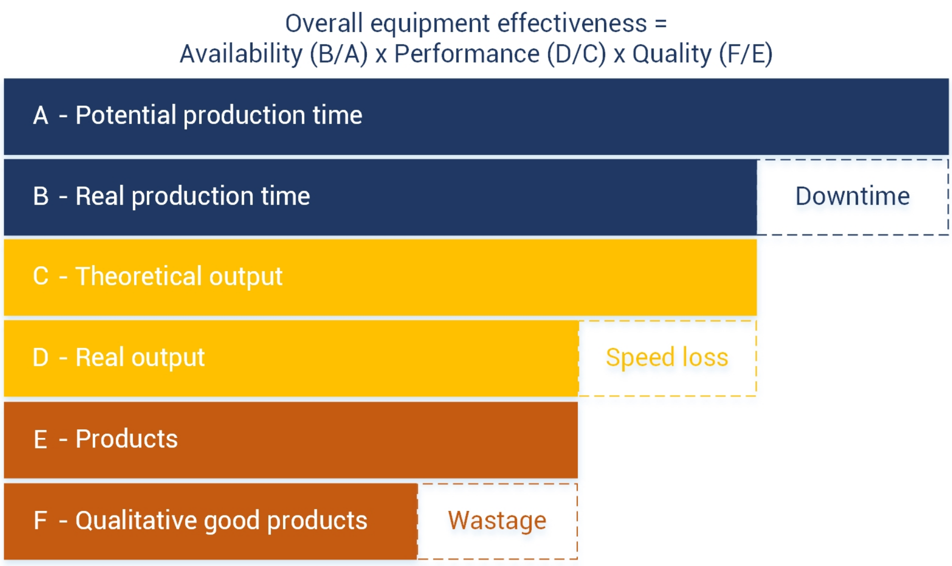


Figure 1.1: **Illustration of the Overall Equipment Effectiveness (OEE). Illustration is based on Nakajima [1982].**

To be able to go into depth, one machine is chosen to be researched. This is the machine with the highest downtime. Currently, the downtimes of the machines are not known. The downtime is analyzed in 3 Downtime analysis. The reasons for the downtime of the machine with the highest downtime, are listed and evaluated with a Pareto analysis. The results of the downtime analysis are discussed with Nelson Pine, after which an attempt is made to solve some of the problems. One of the problems is treated during this internship and described in 5 Downtime improvement: White belt broken/off.

Next to the potential of improvement of the uptime, it is expected that there is a potential in the improvement of the throughput, i.e. theoretical output. This is investigated in 6 Throughput analysis by simulation study by developing a simulation of the sawing machine with the highest downtime.

Chapter 2

Background

Nelson Pine Industries Ltd is a producer of GoldenEdge MDF (medium density fibreboard) and NelsonPine LVL (laminated veneer lumber). It is owned by the Japanese company Sumitomo Forestry Company Ltd.

Laminated veneer lumber is an engineered wood. It is made of multiple layers of veneer, or thin wood, that are adhered together. This creates a product which is more uniform, straighter and stronger than conventional lumber. Next to that it has properties of a composite, making it less vulnerable to warp, twist, bow and shrinkage ([Pine, 2016]). LVL provides a good alternative to solid lumber and steel in structural uses.

MDF is a product made by the combination of wood fibers, wax and resin. MDF is easy to process and is therefore used in a variety of products. The most common application is furniture. See *Figure 2.1* for a flowchart of the MDF production processes at Nelson Pine.

This report focuses on the second last process: the sawing, or panel sizing, of the MDF. Nelson Pine has three sawing machine (A, B and C). As can be seen further in this report, this report is mainly about sawing machine B, or the B-saw. A flowchart of a sawing machine in general can be found in *Figure 2.2*. An illustration of the B-saw can be found in *Figure 2.3*. The processes are shortly explained below.

Infeed: Stacks of MDF boards are put in place by forklift drivers. A stack with a full height is about 900 mm high. This is too high to be cut directly. Therefore, the stack is divided into several parcels. The sheet pusher separates one or multiple sheets from the stack, after which the nip rollers move the sheets on the parceling table. The operator tries to balance the parcels, so the heights of the parcels are as close to one another as possible.

Rip cut: Once all sheets for one parcel are on top of each other, it is rolled to the rip cut area. Here, the parcels are cut in length direction. Once the rip cut machine is done with its previous parcel, the rip cut pusher clamps the parcel. It is aligned, after which it is transported to the rip cut machine. Once at the right position, the rip cut machine starts sawing. After the first cut, the rip cut pusher moves the parcel again to the right position. It is sawn again. This repeats until all cuts are made (typically 2 to 4 cuts).

Cross cut: After all rip cuts are made, the parcel is moved with the white belts to the cross cut. Here, the parcels are cut in width dimension. The same steps as the rip cut are done (typically 2 to 6 cuts).

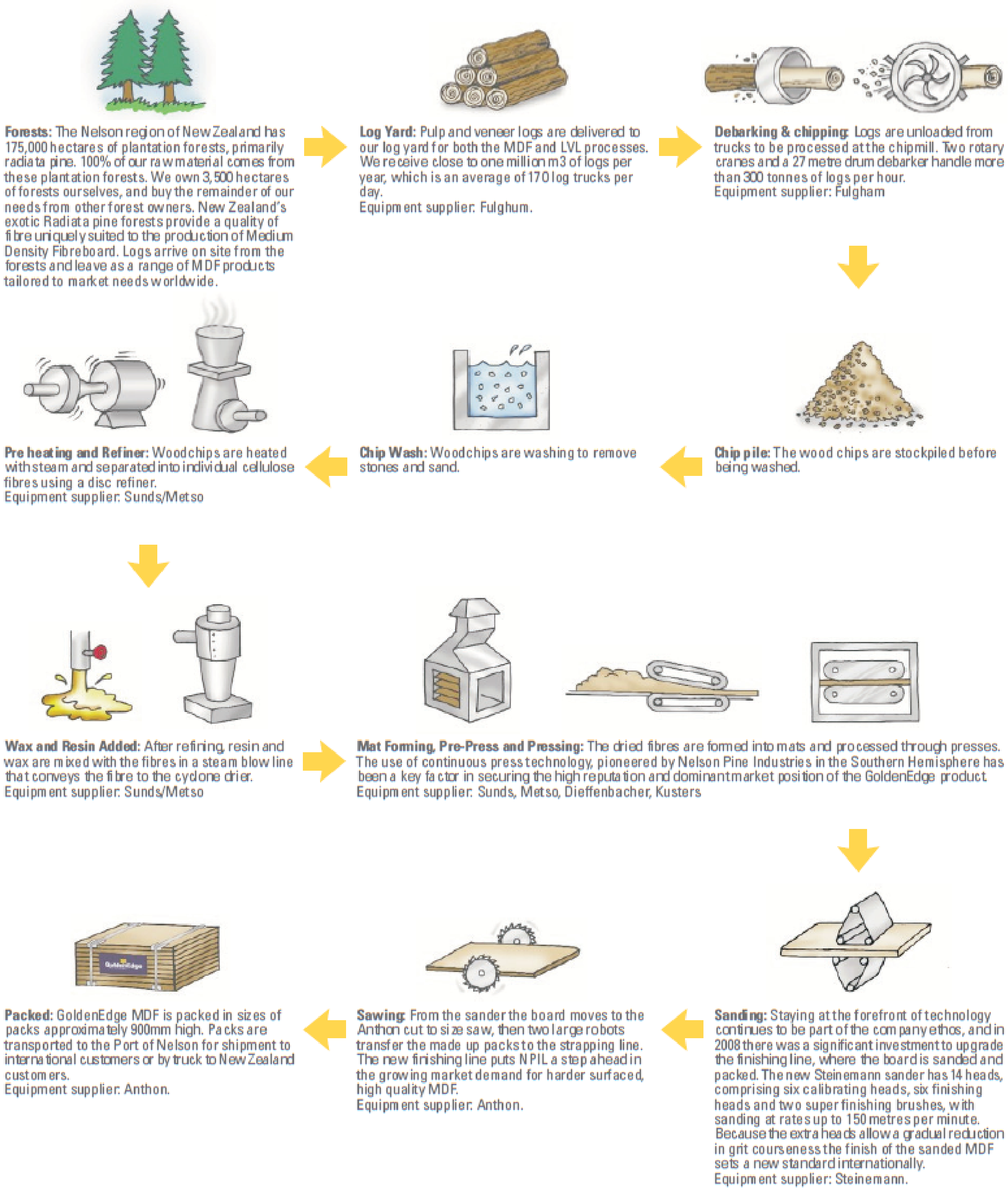


Figure 2.1: **Flowchart of the production of MDF at Nelson Pine.**

Stacking: Once all cross cuts are made, the parcel is moved to the stacking area. Here, the parcels are stacked on top of each other. The parcel is rolled to the cross cut outfeed area. A parcel pusher pushes the parcel on top of the cookietray. The cookietray is a device that is able to place the parcels on top of each other. Once the stack is complete again, the stack is rolled away to the packing area, where the parcels are packed. Packing of the parcels is out of the

Figure 2.2: **Flowchart of the panel sizing machine.**

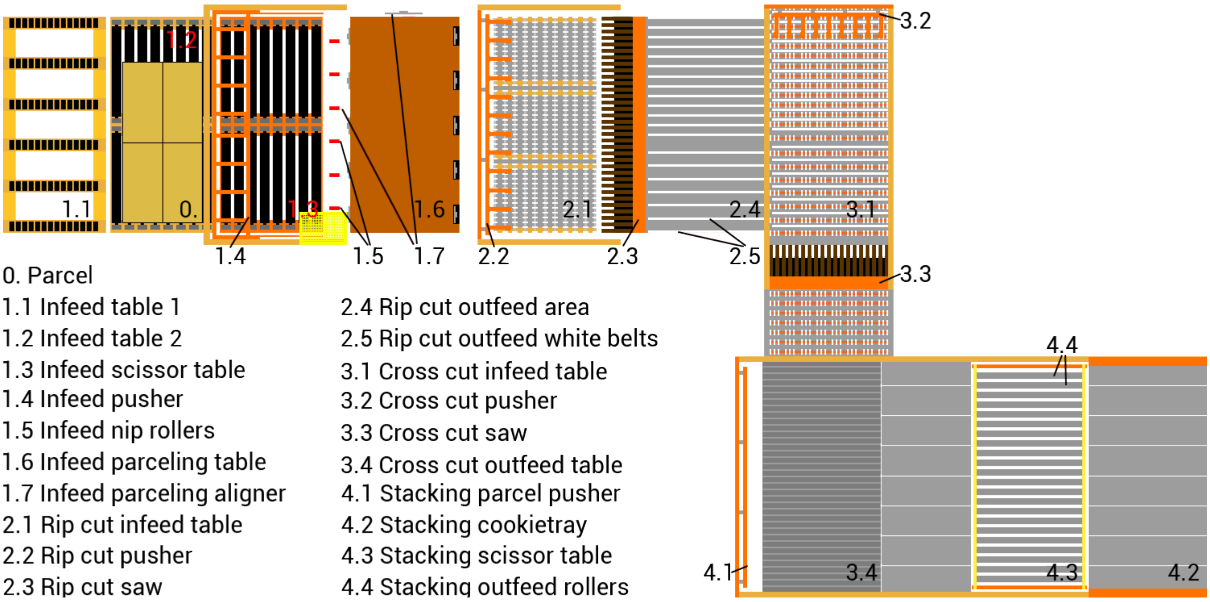


Figure 2.3: **Illustration of the B-saw. The relevant areas and parts are given a name.**

scope of this report.

The sawing machine can cut boards with different length, width and thickness, into boards with the required dimensions for the customer. In total there are 19 different "cut patterns". A cut pattern gives the number of cuts that has to be done in length and width direction. See *Figure 2.4* for an example of a cut pattern.

Every stack comes with a top and bottom "cover sheet". As the name suggests, it is there to protect the other sheets. The cover sheet is also made of MDF.

Some definitions that are used often in this report, and may be confusing, are explained below.

- **Sheet.** A sheet, or board, is one layer of MDF. Nelson Pine produces sheets with a thickness between 2.5 and 30mm, a length of about 3000 to 7500mm and a width of 2510 or 2550mm. The input of the sawing machines, which consist of multiple sheets on top of each other, is called a stack.

- **Parcel.** In the sawing machines, the stacks are divided into several parcels. The process of dividing the stack into parcels, is called "parceling". A stack is divided into parcels to decrease the height. The sawing machines can cut parcels with a maxiumum height of about 200mm.

- **Stack.** Stacks are the input for the sawing machines. They consist of multiple sheets on top of each other. The usual height of a stack is 900mm.

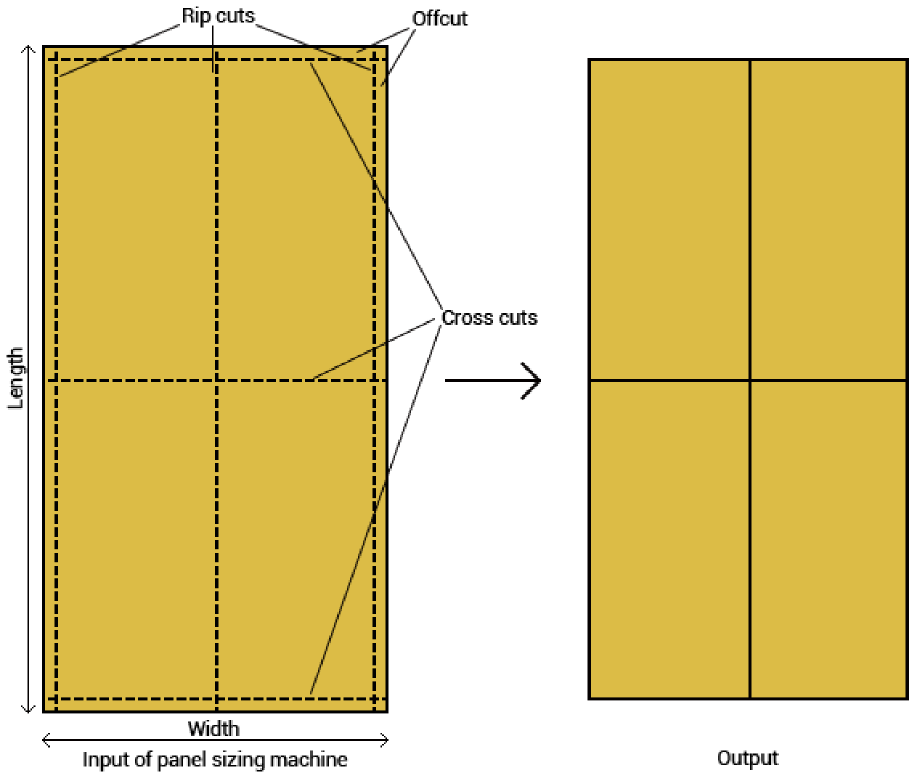


Figure 2.4: **Example of a cut pattern. The striped lines show where cuts have to be made. This cut pattern has 3 rip cuts and 3 cross cuts. This results in 4 packs. The width and length are variable. The offcut is recycled.**

- **Pack.** When stacks are cut into multiple ”stacks”, they are called packs. Also, see *Figure 2.4*. This is the output of the sawing machines, and this is what is sent to the customer after packaging.

Chapter 3

Downtime analysis

3.1 Introduction

The first variable of the overall equipment effectiveness of the sawing machines (see *Figure 1.1*) that is researched, is the downtime. To go into depth, it is decided to find the machine with the highest downtime, and investigate the problems that cause the downtime. For the internship, this is directly a good way to get to know the sawing machines.

3.2 Downtime analysis

To find the machine with the highest downtime, data is used from the past. Only the data of the last year, August 2015 to July 2016, is used. July 2016 is the last complete month at the time of researching the downtime of the machines. The 366 days in that year is assumed to be enough data to determine which saw has the highest downtime.

All three sawing machines have a sensor that records the time that the machine is in operation. For every minute of the day it records whether the machine is on or off. Since it records the data all day, even when the machine is not supposed to be on, it does not give the downtime. The downtime is defined as the time that the machine was supposed to run (the "Potential production time", see *Figure 1.1*), minus the time that the machine was actually running.

The potential production time is not recorded by Nelson Pine. Therefore, the potential production time must be estimated based on the uptime of the machine. One can imagine that when the machine was running for 7.5 hours on a Thursday, it was probably supposed to run for 9.25 hours (7:00 to 17:30, two breaks of 15 minutes, one lunch break of 30 minutes and an extra 15 minutes since it is not expected that the operator is always on time), but had a total downtime of 1.75 hours. The logic that was used to estimate the potential production time, is shown in *Figure 3.1*.

It is decided to use a threshold value of 1 hour. Here the assumption is made that when the machine runs for an hour or less, it is because of a maintenance shut, or another similar reason. Planned maintenance shuts are not seen as potential working time. When the machine runs for more than the nominal number of potential hours per day, it is assumed to be overtime and therefore regarded as potential working time. On a Friday, the normal number of potential hours is 1.5 hours lower, because the operator is supposed to clean the machine for 1.5 hours.

The results are displayed in *Figure 3.2*. As can be seen, the B-saw has the lowest uptime. Therefore, the B-saw will be researched further from this point on. The reasons for the downtime of

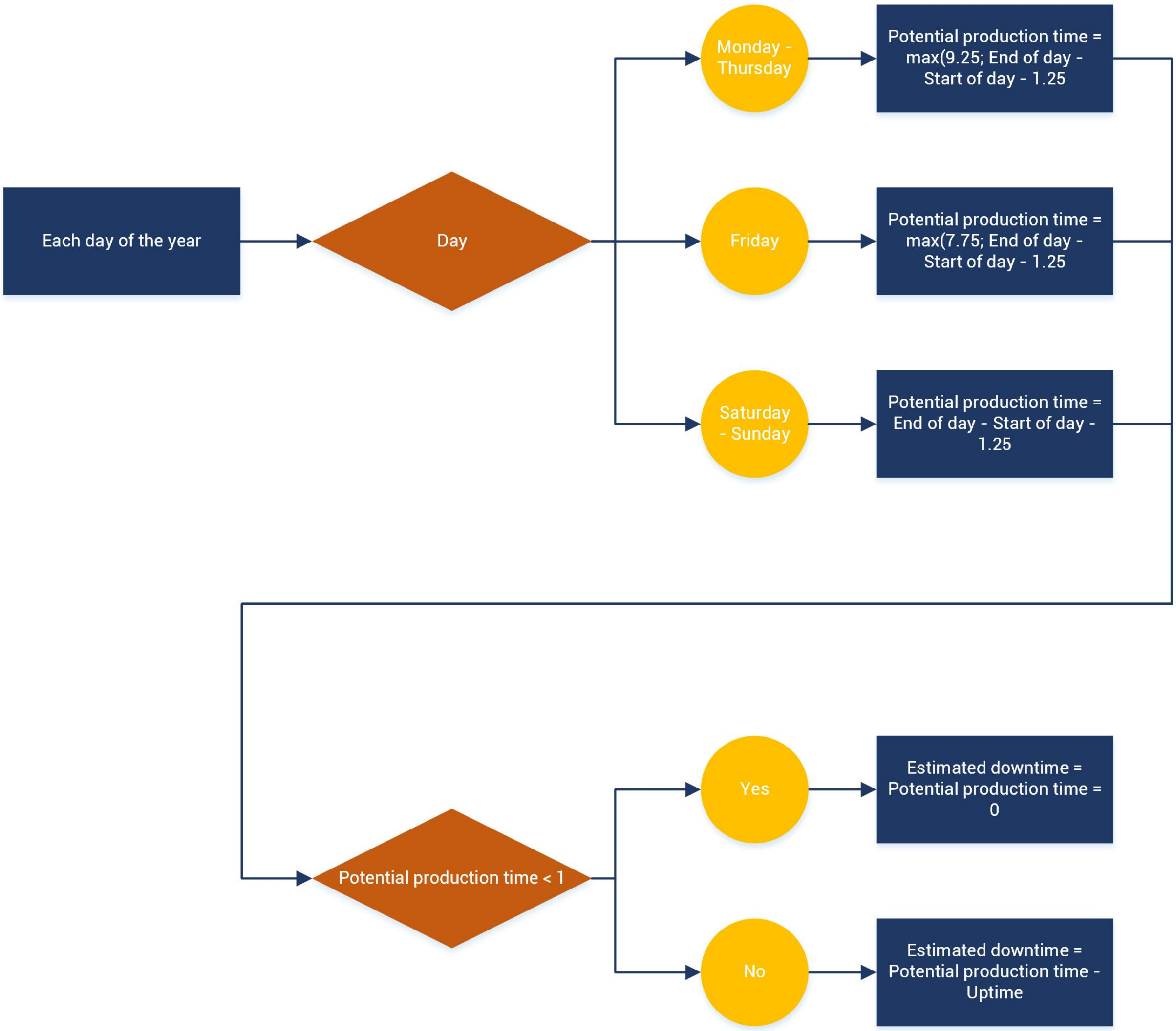


Figure 3.1: **Conditional diagram to estimate the potential working time from the number of hours that the B-saw was running.**

the B-saw will be researched in the next subsection.

3.3 Pareto analysis on downtime reasons

There are two sources where information about breakdowns is recorded. The first is a diary of the operator, in which he is supposed to write down all breakdowns. The other source is Pirana. Pirana is used by the maintenance department to plan maintenance activities, and to record the maintenance activities done. Data is extracted from both sources for the period from August 2015 until July 2016. Generally, Pirana gives an estimation how long the machine was down. The operator, however, generally does not write down the time the machine was down. For the breakdowns which have no information about downtime, the operator or an expert of maintenance is asked to give an estimation. All breakdowns are grouped. A summary of the statistics is given in *Figure 3.3*.

The downtime of the groups of breakdowns is plotted in a Pareto chart. See *Figure 3.4*. As can be seen, the Pareto chart does not follow the 80/20 rule, which says that 20% of the reasons

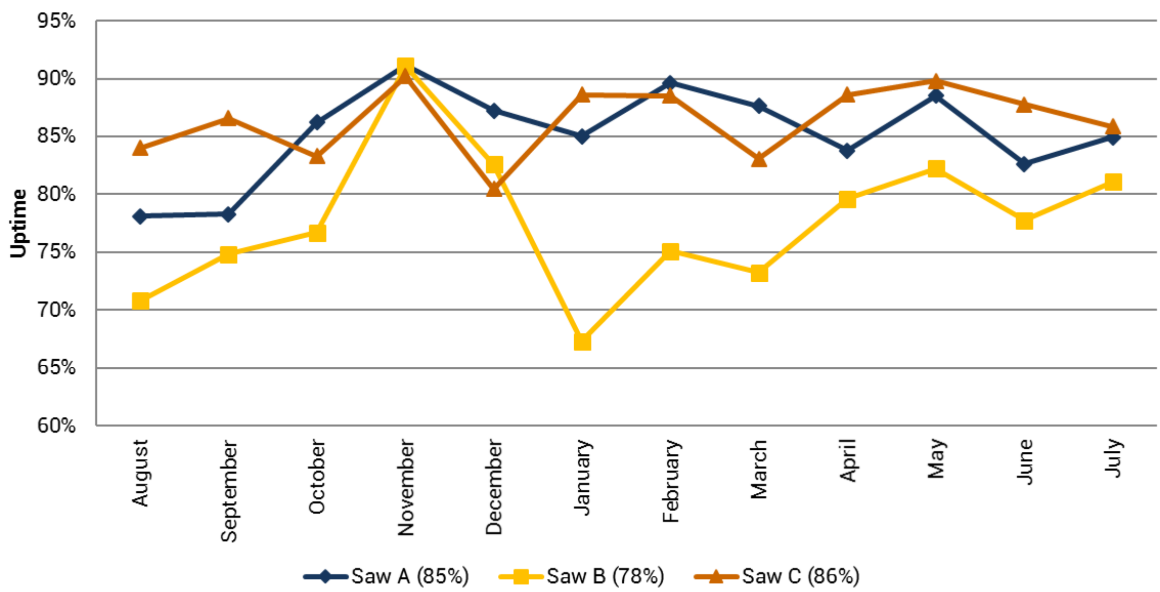


Figure 3.2: **Uptime percentages of the three sawing machines in the period from August 2015 to July 2016. The average uptime over the year is given in brackets in the legend.**

Figure 3.3: **Statistics of the B-saw in the period from August 2015 until July 2016.**

account for 80% of the downtime. However, the top ten reasons do account for about 40% of the total breakdown. These ten reasons are analysed further.

The change over the year of the top ten downtime reasons can be seen in *Figure 3.5*. Together with Mark Peek (Mechanical Supervisor), Ben Pitcaithly (Electrical Technician), John Hughes (Maintenance Fitter Sawing and Packaging) and Caleb Denmead (Mechanical engineer manager, internship supervisor), the ten reasons are discussed. The conclusions of the meeting are given below.

- **Rip cut pusher not lifting, improvement required.** The problem is known, several causes are suspected. During the internship, this problem is solved.
- **Cross cut pusher not working, fixed.** The problem is fixed. This is in accordance with *Figure 3.5*.
- **Strapping line down, out of scope.** The strapping line is another department. When the strapping line is down, the products will pile up after being sawn until the line is full. This problem is relevant for improving the uptime of the B-saw, but out of scope of the internship.
- **Rip cut scribe not working, (consider it) fixed.** The problem is known, but it was not apparent that it had caused so much downtime. It was expected not to be a big problem

again in the future. However, when the rip cut scribe saw starts having problems again, action might be necessary.

- **White belt broken (/off), improvement required.** Reasons are suspected why the white belts gets knocked off or break. Read 5 Downtime improvement: White belt broken/off about how this problem is solved.
- **Cross cut offcut pusher not working, fixed.** A lot of work has been done on the cross cut offcut pusher, this is reflected in *Figure 3.5*.
- **Third party changed settings, work in progress.** The problem is known and Nelson Pine is working on the problem.
- **Rip cut pressure beam not working, improvement required.** The problem is assumed to be caused by the same reason as “Rip cut pusher not lifting”. No further analysis will be done until it is apparent that it has another cause. During the internship, this problem did not occur again, and is therefore discarded.
- **Rip cut aligner (shark fin) not working, (consider it) fixed.** Work has been done on the rip cut aligner. It is expected that the problem will not occur again.
- **Cross cut aligner not working, (consider it) fixed.** The problem should not occur anymore, since a new motor is installed recently. Therefore, it is considered fixed.

3.4 Conclusion

The downtime of one year of the B-saw is inspected. The top ten reasons, that are estimated to account for 40% of the downtime, are analysed together with Nelson Pine. For five out of the ten problems, it is expected that the problems are solved. Three downtime reasons require improvement. One requires improvement but is out of the scope, and the last remaining downtime reason is being fixed.

The downtime analysis done in this internship provides a good overview of the downtime reasons. Tasks were given to employees to work on most of the remaining problems. This should decrease the downtime of the B-saw. However, an analysis like this should be done regularly, and preferably more accurate (whereas this analysis relies a lot on assumptions and estimations). In that case Nelson Pine would be able to continuously assign tasks to the most important problems, and record whether these problems are solved after assigning tasks to solve the problems. The machine would then be able to process more MDF, and since problems will occur less frequently, the maintenance staff would have more time left to focus on the remaining problems to further reduce the downtime.

To facilitate such a culture of continuous improvement, an automatic downtime analysis system is implemented in the B-saw. Every time the machine stops for a consecutive time of five minutes, the operator must assign a downtime reason associated with the stop. The system is described in more detail in 4 Downtime analysis system.

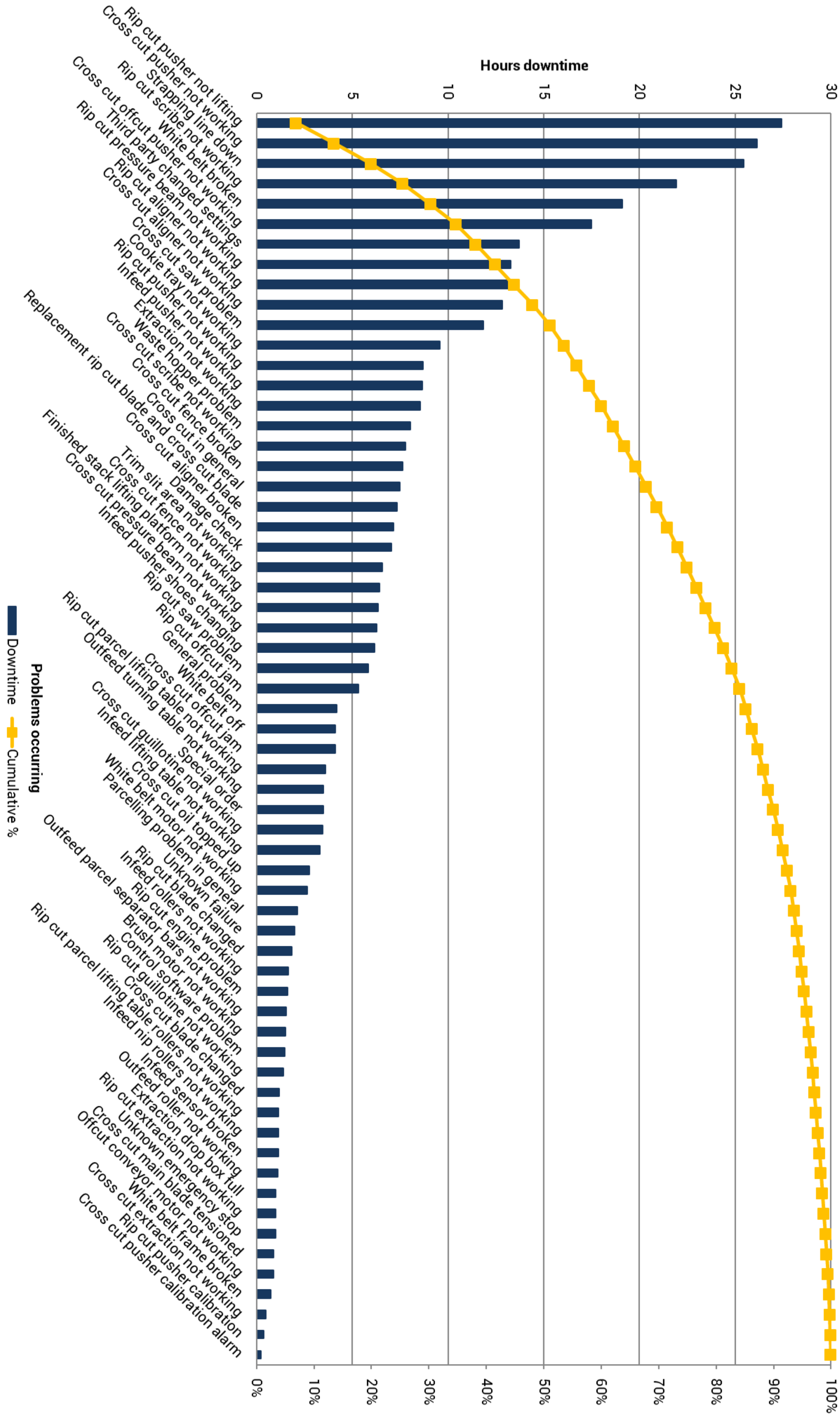


Figure 3.4: **Pareto analysis on the breakdowns of Saw B in the period from August 2015 until July 2016.**

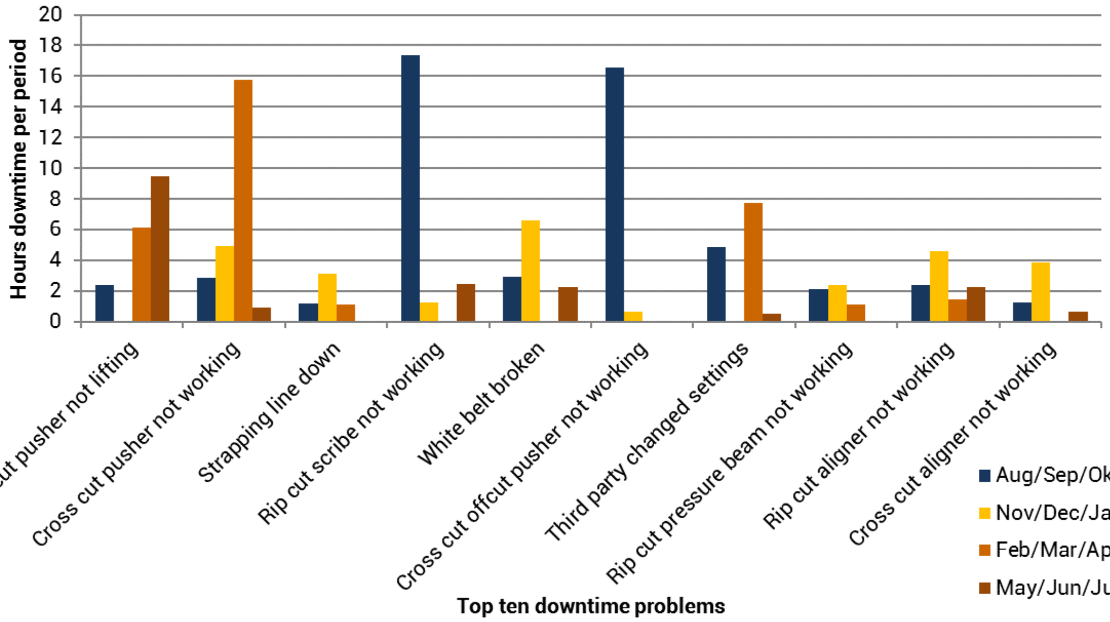


Figure 3.5: **The change of the top ten downtime reasons over the year.**

Chapter 4

Downtime analysis system

4.1 Introduction

In 3 Downtime analysis the downtime of the B-saw was analyzed. The downtime was estimated by the uptime information of the B-saw. The downtime reasons were evaluated and estimated how much time they cost. With the corresponding Pareto chart of the downtime reasons, tasks were assigned to the most important problems.

To continue facilitating the downtime information, and thereby stimulating a culture of continuous improvement, a system which records the downtime events is installed on the B-saw. This system is shortly described in this chapter. This downtime analysis system was already available at the LVL plant within Nelson Pine, and is therefore not developed during this internship. During this internship, help was offered with the implementation of the system, and adjustments were made in the system so it fitted the B-saw.

4.2 Downtime analysis

The interface the operator of the B-saw sees is given in *Figure 4.1*. After every instance the B-saw is down, the operator is asked to fill in the reason for the downtime. This information is saved in a database.

The database is able to show reports of the downtime and corresponding downtime reasons. Examples of two relevant reports are given in *Figure 4.2* and *Figure 4.3*.

4.3 Conclusion

With the implemented downtime analysis system, downtime data is gathered of the B-saw, and can be accessed anytime. The reports can, for example, be used weekly during the ”Sanders and saws meeting”, to present the downtime of the past week and to determine if any actions must be taken to solve problems. Also, downtime data over a longer period of time can be evaluated to gain a clearer picture of the downtime events. For example, a downtime reason may result in a low downtime within a week, but when it occurs more frequently in three months than other reasons, it could be one of the highest downtime reasons in that period (i.e. action should be taken after all).

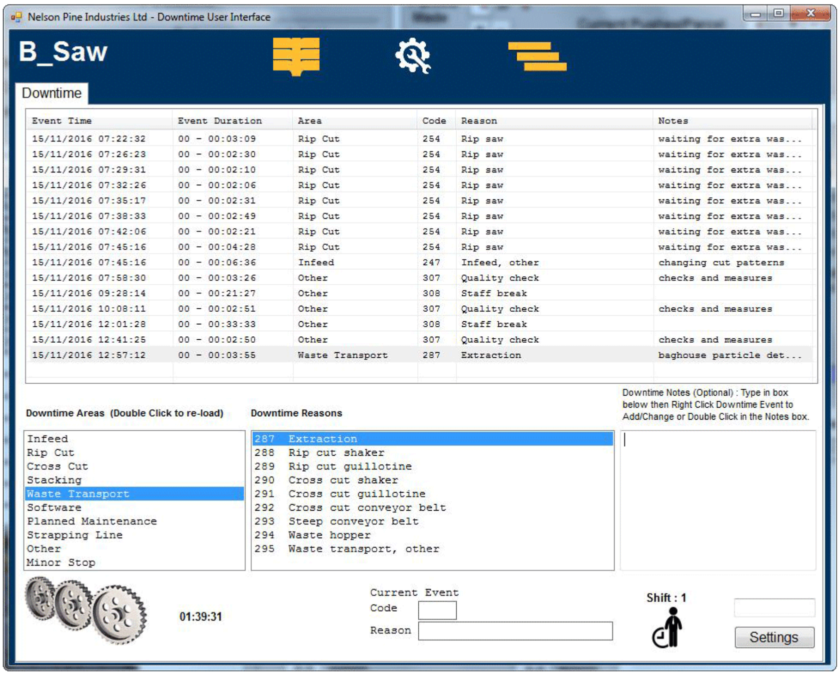
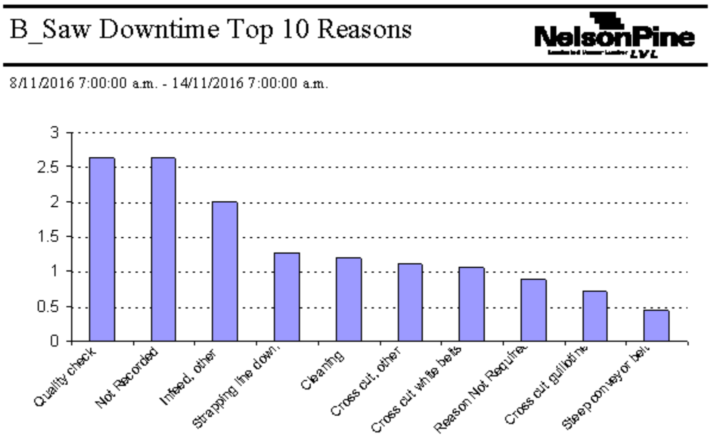


Figure 4.1: **Interface of the downtime analysis system on the operator computer of the B-saw.**


B_Saw Downtime Top 10 Reasons

8/11/2016 7:00:00 a.m. - 14/11/2016 7:00:00 a.m.

Reason	Hours	Event Count
Quality check	3	23
Not Recorded	3	13
Infeed, other	2	11
Strapping line down	1	2
Cleaning	1	1
Cross cut, other	1	4
Cross cut white belts	1	1
Reason Not Required	1	21
Cross cut guillotine	1	2
Steep conveyor belt	0	1

Figure 4.2: **Example of a report of the downtime of the B-saw. This report shows the Pareto analysis.**

B_Saw Downtime Events

8/11/2016 7:00:00 a.m - 14/11/2016 7:00:00 a.m

			Count	% of DT	Duration
				100.0%	86:50
Cross Cut				2.7%	2:21
Cross cut white belts			1	1.2%	1:02
	09/11/16 8:59:32	1:02:59			
Cross cut, other			4	1.3%	1:06
	10/11/16 8:21:30	0:10:43 dust problems			
	10/11/16 9:24:09	0:43:51 dust problems			
	10/11/16 10:40:14	0:07:26 dust problems			
	10/11/16 11:14:14	0:04:37 dust problems			
Cross saw			3	0.2%	0:11
	10/11/16 13:30:01	0:02:32 dust problems			
	10/11/16 13:46:06	0:03:25 dust problems			
	10/11/16 14:00:14	0:05:34 dust problems			
Infeed				2.8%	2:26
Infeed board pusher			3	0.3%	0:15
	09/11/16 11:10:58	0:07:36 sides and ends			
	09/11/16 11:30:23	0:06:19 sides and ends			
	09/11/16 16:19:35	0:01:50 sides and ends			
Infeed coversheet stops			1	0.2%	0:12
	09/11/16 17:18:03	0:12:00 no board to cut			
Infeed, other			11	2.3%	1:59
	08/11/16 9:07:03	0:03:43 waiting for board			
	09/11/16 8:03:37	0:01:35 finding board to cut			
	09/11/16 13:23:19	0:24:05 waiting for board to cut			
	09/11/16 14:02:36	0:41:22 waiting for board to cut			
	09/11/16 15:49:57	0:04:57 waiting for board to cut			
	09/11/16 16:10:20	0:00:44 waiting for board to cut			
	10/11/16 7:00:02	0:26:03 waiting for board			
	10/11/16 13:08:26	0:01:48 changing between works orders			
	10/11/16 16:08:22	0:03:19 sides and ends			
	11/11/16 9:04:24	0:05:53 changing between works orders			
	11/11/16 11:12:47	0:05:43			
Minor Stop				1.0%	0:53
Reason Not Required			21	1.0%	0:53
	08/11/16 9:00:45	0:00:12			
	09/11/16 11:44:40	0:00:23			
	10/11/16 14:17:18	0:00:25			
	11/11/16 11:29:02	0:00:15			
	11/11/16 15:36:35	0:02:43			
	11/11/16 15:42:04	0:02:51			
	11/11/16 16:01:51	0:04:00			
	11/11/16 16:38:54	0:02:09			
	11/11/16 17:30:00	0:00:34			
	12/11/16 7:11:36	0:03:11			
	12/11/16 7:15:13	0:02:18			
	12/11/16 7:31:17	0:02:07			

Figure 4.3: **Example of a report of the downtime of the B-saw. This report shows individual downtime reasons. Note that this is only a part of the report.**

Chapter 5

Downtime improvement: White belt broken/off

5.1 Introduction

One of the ten main breakdown problems, as described in 3 Downtime analysis, is the white belts that get knocked off or break. This mainly happens when a parcel lies with the edge on the long side, on half of a white belt (see *Figure 5.2*). To make sure the parcel is fully on a white belt, or not at all, Nelson Pine in the past introduced so called “infeed blocks”, which are used at the parceling station. There are two types: 50mm and 100mm. See *Figure 5.1a* for a sketch of the situation without the infeed blocks, and *Figure 5.1b* for a sketch of the situation with infeed blocks. The parcels are pushed against the infeed blocks, instead of against the wall. The blocks cause the parcel to shift away from the wall, in the y-direction. The blocks are inserted manually by the operator, when the operator thinks it is necessary.

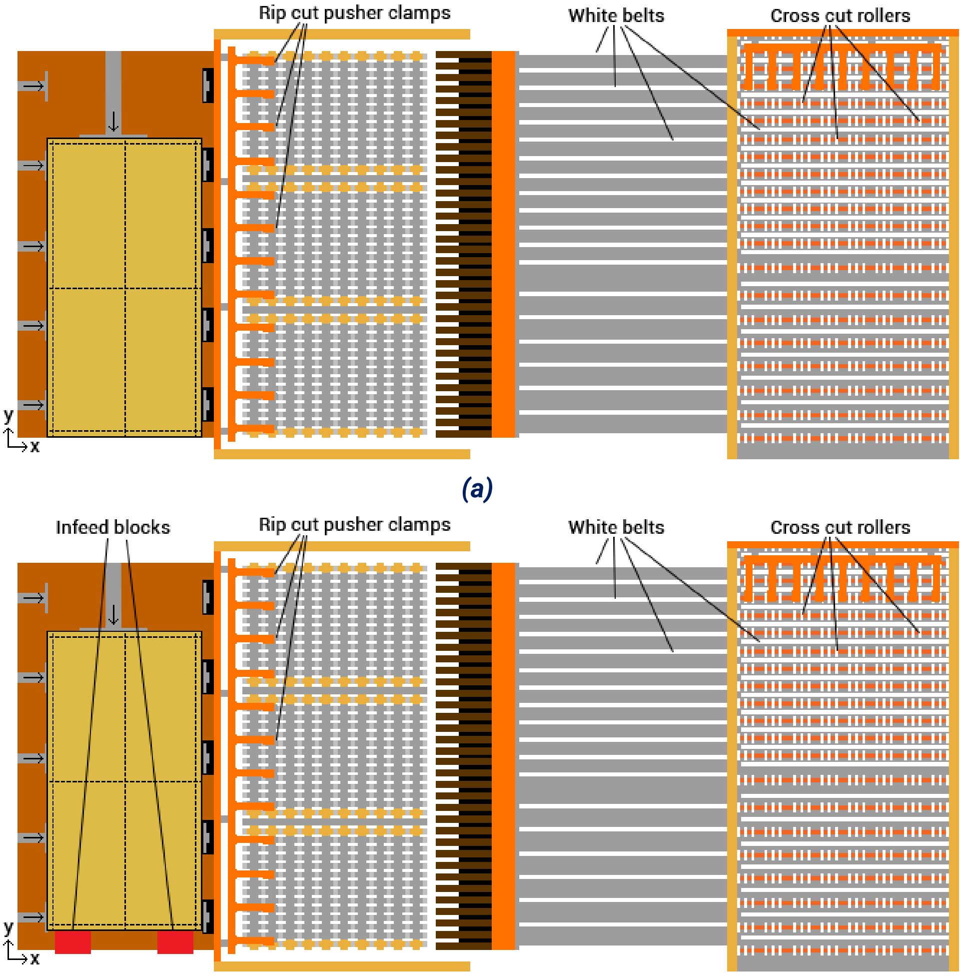
Since it is done manually, Nelson Pine decided to implement a system which detects whether the correct infeed block is used (none, 50mm, or 100mm). The task of determining which block to use for each different length of input stacks, is given to me.

The calculation should, next to making sure that the end of the parcel is not on top of a white belt, take two more factors in account. The second factor it should take into account, is that the rip cut pusher clamps clamp the board with at least 50% of its width. In a situation where it just clamps the board could damage the board by applying the clamping force on an area that is too small. See *Figure 5.3* for illustrations of a situation where the board is clamped OK, and a situation where the board is not clamped OK.

The third factor the calculation should take into account is the following. When parcels are situated at the cross cut area, they lie on rows of rollers. This can be seen in *Figure 5.1*. The MDF boards are flexible, especially thin board. Therefore, the more the end of the parcel lies away from a row of rollers, the more it hangs down. The more it hangs down, the more likely it is that the cross cut pusher clamp hits the board and damages it. See *Figure 5.4*. The closer the end of the parcel lies from a roller, the better.

5.2 Model current situation

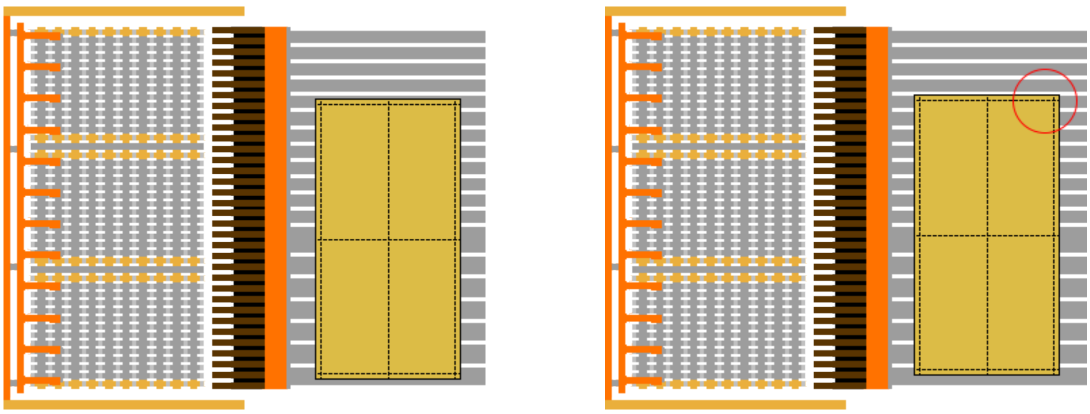
A model is made in Excel. For every length of board that is known, it is determined which block should be used. In the first instance, it discards the blocks with which the parcel lies with its



(a)

(b)

Figure 5.1: **(a) Sketch of the situation without infeed blocks. (b) Sketch of the parceling station with infeed blocks. The sheet has now moved up in y-direction. Note that the dimensions are not corresponding exactly to reality.**



(a) *(b)*

Figure 5.2: **Illustration of the problem that the end of the parcel rests on a white belt. This causes issues with the white belts. (a) OK (b) NOT OK**

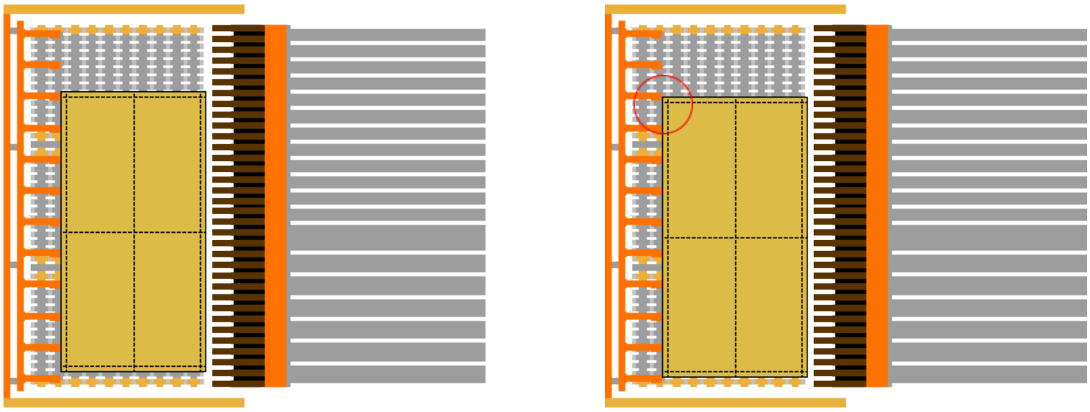


Figure 5.3: **Illustration of the problem that the rip cut pusher clamp clamps the parcel with less than 50% of the width of the clamp. (a) OK (b) NOT OK**

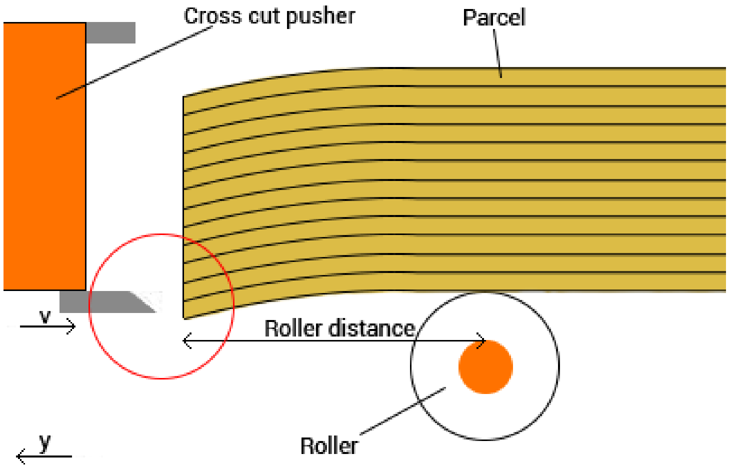


Figure 5.4: **Illustration of the problem that the cross cut pusher clamp damages the parcel, because the parcel overhangs too much. The bigger the "roller distance" is, the more the parcel overhangs. This especially happens with thin boards. The roller distance should be minimized.**

short end directly on a white belt, and/or where the pusher clamp clamps the board with 50% or less of the pusher clamps' width. From the blocks that are not discarded, it chooses the block with which the parcel lies away least from the cross cut rollers. A table of which blocks to use in which situation is given in A Infeed block results in the appendix.

5.3 Linear optimization model

To go a step further, it is decided to research how much improvement can be made by changing the widths of the infeed blocks. A motivation to research this, is that the current infeed blocks are two separate blocks. These blocks do not cover the full length of the wall. According to Nelson Pine, this sometimes causes issues with the boards that are moved on the parceling table. In some situations, the board hits the left side of the right infeed block, as in *Figure 5.1b*. This causes damage to the boards. Nelson Pine would rather have blocks with which there is no spacing between the blocks. In case they would indeed change blocks which cover the full length, it is convenient to have blocks with the right width.

A linear optimization model is made in Excel to determine what the widths should be in case Nelson Pine would produce new blocks. A comparison between the original situation and the situation with optimized blocks, is given in *Figure 5.5*. The situations are compared to each other in terms of the length away from the roller. In both situations, the blocks satisfy the first two constraints: no parcel end lies on top of a white belt, and no parcel is clamped with 50% or less of the width of the pusher clamp.

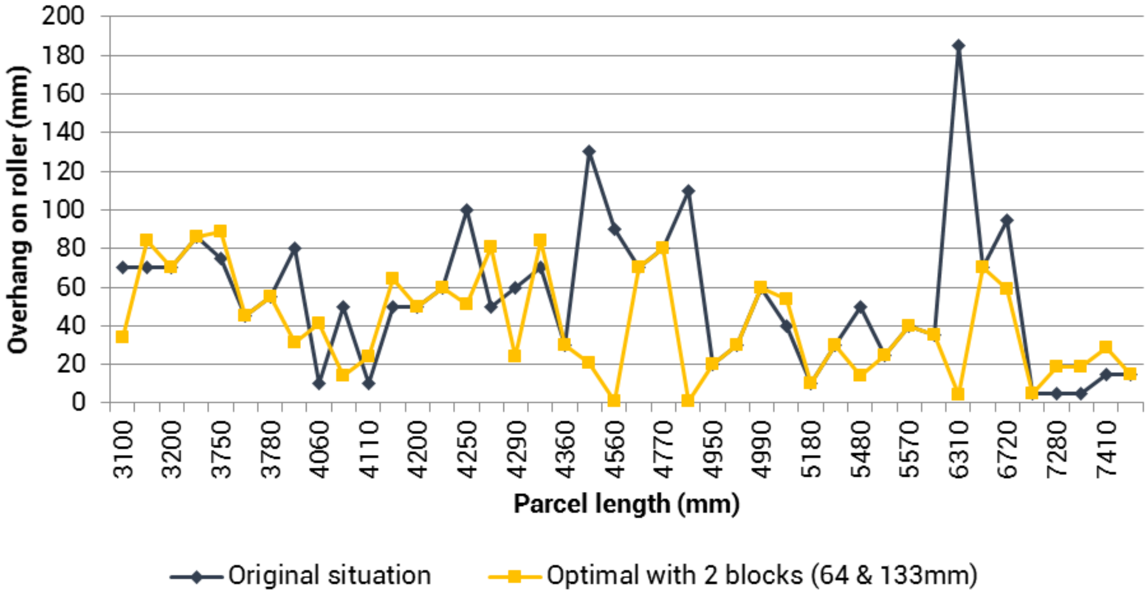


***Figure 5.5:* Comparison of the overhang on the cross cut rollers between the original situation, and the situation with two blocks with an optimal width. Note that not all parcel lengths are given, for reasons of spacing.**

As can be seen, some peaks are removed with the optimized situation, and the yellow line in general is below the blue line. Nelson Pine is convinced that it would be better than the original situation. The situation with two optimized blocks is also compared to an optimized situation with three blocks (*Figure 5.6*), and a situation where the width of the block could be change to any size (*Figure 5.7*). The last, however, would be a big investment.

Having a situation with three optimal blocks changes the overhang insignificantly. A situation with a block that can be changed in width to any size, does have quite a big impact. However, it still has some peaks in the range of 80-90mm. Together with the fact that such a system would be a big investment, it is decided not to continue with this system. It is, however, decided to go ahead and produce two blocks with optimal widths and which cover the full length.

5.4 Implementation

The current infeed blocks are about 300mm wide, made of steel and weigh about 15kg each. New infeed blocks which must cover the full length (about 2200mm), would weigh too much to carry, when they would be made of steel. A material is required which still has a lot of strength, but which is a lot lighter. Conveniently, Nelson Pine is also a producer of LVL. LVL has similar strength characteristics as steel, but has a much lower density (roughly 500 $\mathrm{kg/m^3}$ compared to 8000 $\mathrm{kg/m^3}$). A model of the infeed blocks is made in Autodesk Inventor. A picture of the model is given in *Figure 5.8*. The metal rod serves to place the block on the parceling table. See *Figure 5.9* for a picture with the infeed block inserted.

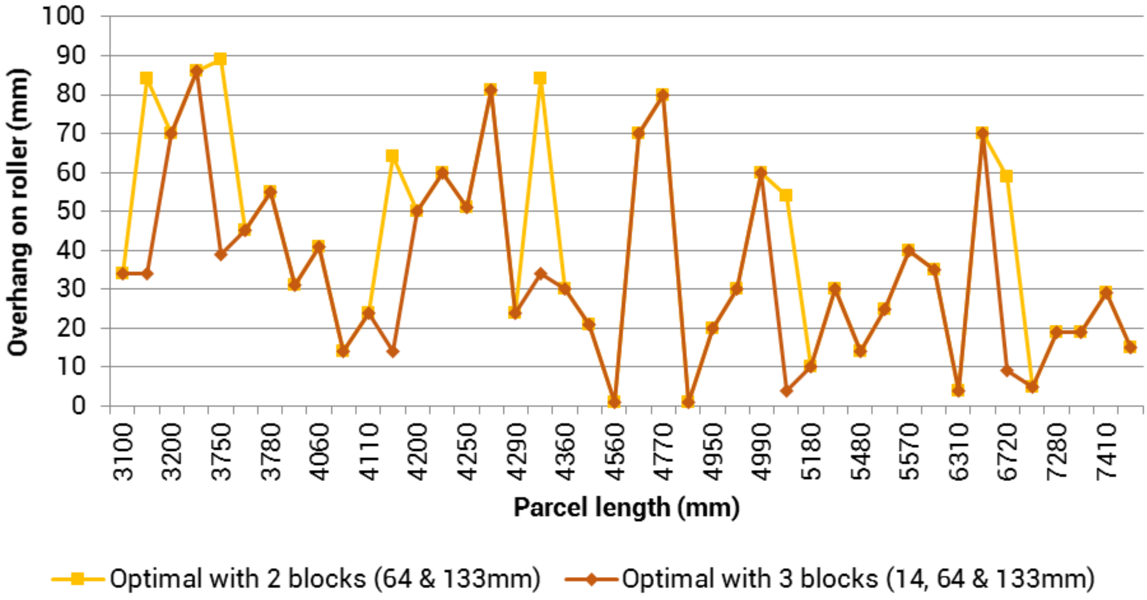


Figure 5.6: **Comparison between the situations with two optimal blocks and three optimal blocks. Note that not all parcel lengths are given, for reasons of spacing.**

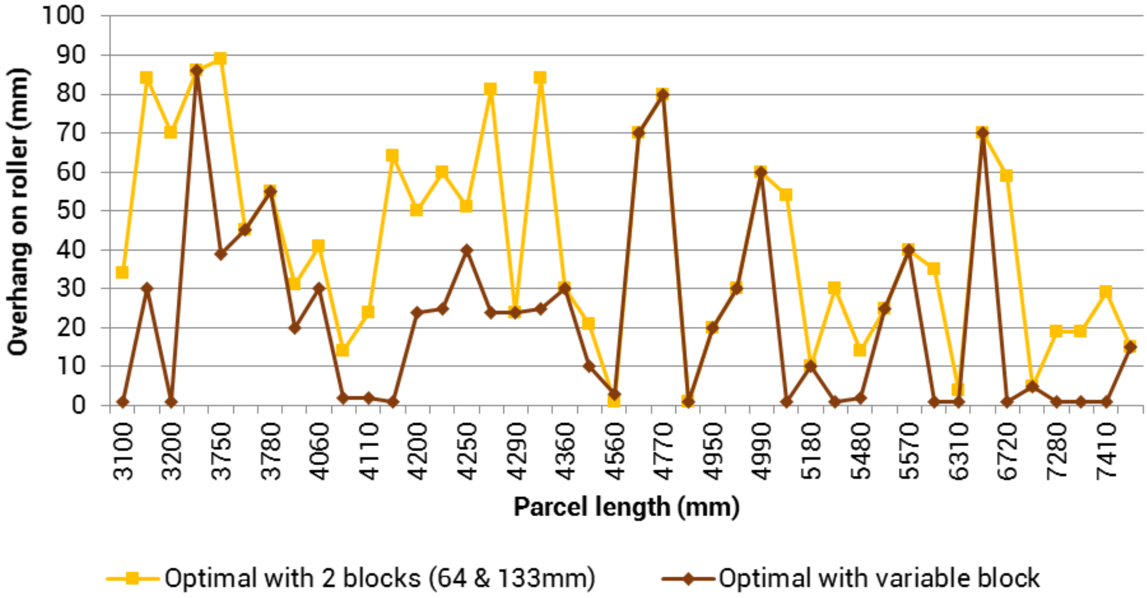


Figure 5.7: **Comparison between the situations with two optimal blocks and a block with variable width. Note that not all parcel lengths are given, for reasons of spacing.**

Nelson Pine implemented a sensor which detects whether no block, the 64mm block, or the 133mm block is used. In combination with a provided table which shows which block should be used for which length of board, it can be checked whether the correct block is used. This list is also developed with Excel. The list is based on the lengths of board which were processed last year. In case a new length appears, the operator is told to contact an electrician to calculate which block should be used for this new length. This is done with the model in Excel.

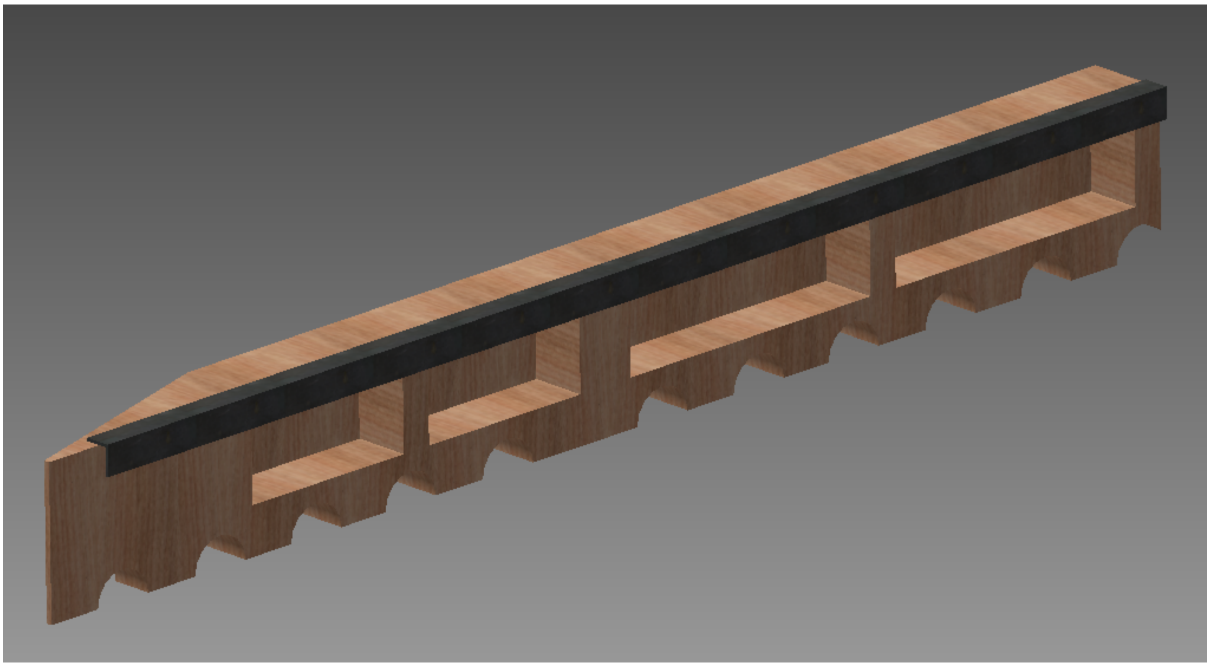


Figure 5.8: **Infeed block in Autodesk Inventor. This block has a width of 133mm. The other block has a width of 64mm.**

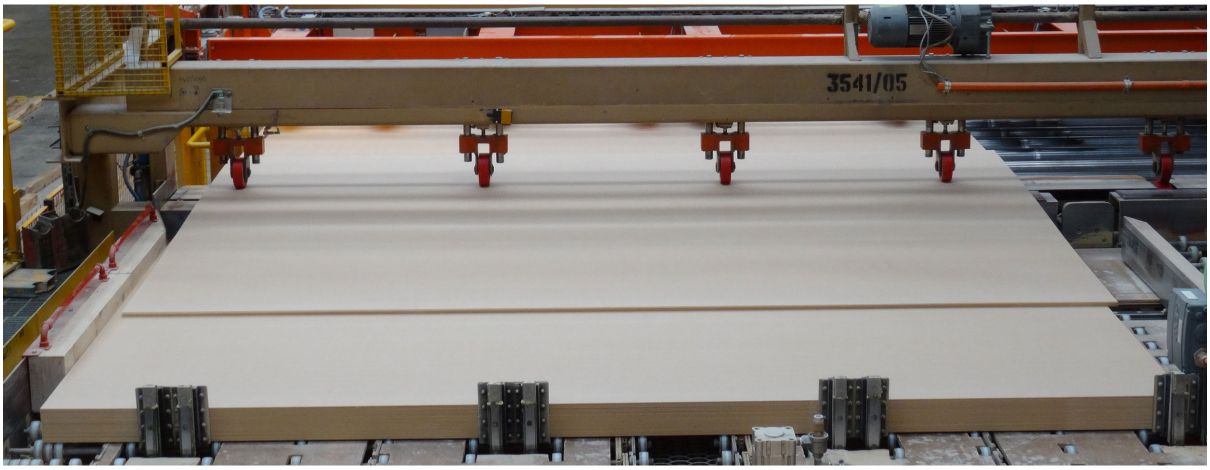


Figure 5.9: **Infeed block 133 mm used for sawing board with a length of 4050 mm.**

It would be more convenient if the calculations are done directly by the PLC (programmable logic controller) of the B-saw. However, since it is expected that it is hard to implement the calculations in the PLC, it is decided by Nelson Pine not to spend time on the implementation of the calculations. Next to that, Nelson Pine expects a low number of new lengths.

5.5 Conclusion

By making sure that an infeed block with the correct width is placed at the parceling station, multiple problems are solved. First of all, the problem with the white belts should be solved. Next to that, quality issues are avoided with the clamp causing damage. Finally, quality issues with the cross cut pusher stabbing the board are avoided. This will not only result in a higher quality product. The strapping line has to remove damaged boards, which causes downtime at the strapping line. Downtime at the strapping line is one of the main causes for the downtime at the sawing machine (see *Figure 3.5*). Concluding, the infeed blocks reduce the downtime of the sawing machine in several ways, directly and indirectly.

Chapter 6

Throughput analysis by simulation study

6.1 Introduction

Where the breakdown analysis (done earlier during this internship) was focused on increasing the uptime, this analysis is focused on increasing the throughput, or the theoretical output (see *Figure 1.1*), of the B-saw.

The throughput is increased by removing bottlenecks. However, since there is a big variety of stacks that goes in the machine, and what comes out, there is no clear bottleneck (this will be explained more thoroughly in the following section). Therefore, it is chosen to develop a simulation study of the B-saw. The goal of the simulation study is to find an overall bottleneck. Once the overall bottleneck has been found, the time of the bottleneck will be decreased in the simulation, to be able to find the next bottleneck. This can be repeated for a number of times.

Nelson Pine has electricians available to change the programmable logic controller (PLC) of the B-saw. Some processes can be altered, interchanged, or increased in speed to increase the speed of the machine. Ideally, only changes in the PLC are to be made to increase the throughput of the machine.

Since the strapping line should be able to keep up with the B-saw, the effect on the cycle time of the packs going to the strapping line is studied as well.

6.2 System description

An illustration of the B-saw can be found in *Figure 2.3*. The figure displays all relevant names of the areas and parts. A list of all relevant processes can be found in *Table 6.2*.

The machine is controlled by programmable logic controller software. To develop a simulation, it is necessary to use the same logic control. It is decided to observe the machine and thereby determine what the logic control is, instead of unravelling the programming code. The flowcharts of the logic control are shown in B PLC flowcharts in the appendix.

From the PLC, together with some tests in the simulation, it is determined that there are five locations where the bottleneck can be: the infeed, the rip cut, the front cross cut, the back cross cut, and the stacking. See *Table 6.1*, to see which processes belong to which bottleneck. In other words, to reduce the bottleneck, one can reduce the process time of one of the activities related to that bottleneck.

The activities in the table are based on the current process times. Care should be taken with the decision which activity process time is decreased. For example, currently, the rip cut pusher gets to its home position at the same time as the parcel arrives at the rip cut infeed table. When reducing “2.1 Rip cut infeed table rolls in parcel” or “2.6 Rip cut pusher retreats”, both must be reduced to influence the cycle time.

See the PLC flowcharts which constraints should be satisfied for each area. It is recommended to run the simulation again to find out the real effect of a change.

Bottleneck area	Relevant activities
Infeed	1.1 Infeed pusher pushes group of sheets from stack
	1.2 Infeed pusher retraction
	1.3 Infeed nip rollers move group to parceling table
	1.6 Infeed parceling aligner aligns parcel
	1.7 Infeed parceling table moves parcel to rip cut
	1.8 Infeed parceling table retreats
	1.9 Infeed scissor table (empty) moves down
	1.10 Infeed scissor table rolls in new stack
	1.11 Infeed scissor table (full) moves up
Rip cut	2.1 Rip cut infeed table rolls in parcel
	2.2 Rip cut saw front cut
	2.3 Rip cut saw extra cut
	2.4 Rip cut saw back cut
	2.6 Rip cut pusher retreats
Front cross cut	3.1 Cross cut saw front cut
	3.4 Back cross cut cut delay before pusher retreats
	3.6 Cross cut pusher retreats
Back cross cut	3.2 Cross cut saw extra cut
	3.3 Cross cut saw back cut
	3.5 Cross cut outfeed rollers move parcel to stacking
	4.1 Stacking parcel pusher pushes parcel on cookie tray
Stacking	4.3 Stacking cookietray (full) moves parcel on scissor table/stack
	4.5 Stacking scissor table (half full) moves down
	4.6 Stacking scissor table (full) moves down
	4.7 Stacking scissor table (empty) moves up
	4.8 Stacking outfeed rollers move stack to packing area

***Table 6.1:* Relevant activities for each bottleneck area. To reduce one of the bottlenecks, the process time of one or more of the relevant activities should be reduced.**

A description of the simulation model is given in C Simulation model in the appendix.

6.3 Machine input and overall bottleneck

One can imagine that a cut pattern with a high number of cross cuts, compared to rip cuts, will result in a bottleneck at the cross cut area. A cut pattern with a high number of rip cuts, compared to cross cuts, will result in a bottleneck at the rip cut area. As one can note, the bottleneck is dependent on the cut pattern. That is why an overall bottleneck must be found, incorporating all possible cut patterns.

The input of the simulation is based on the input of last year, provided by Nelson Pine. 241 different pack types were produced in the last year, with a total number of 28,068 packs. For 12 different pack types, with a total of 812 packs, it is unclear what the corresponding input stack is. These are removed from the list. The remaining input list can be found in E Simulation input in the appendix.

For every input, the cycle time of one stack is measured in the simulation. The cycle time is defined as the time it takes from the moment a stack is started to be processed, until the moment when the next stack is started to be processed. The key performance indicator of the simulation is the weighted average cycle time of the 229 stacks. The number of stacks, or percentage of stacks, is the weight factor.

Once the simulation has calculated the weighted average cycle time, it will decrease the infeed area by one second. It will now calculate the weighted average cycle time again. Next, it will increase the infeed area by one second again, and now decrease the next area, the rip cut area, by one second. It again calculates the weighted average cycle time. This is done for each area. The area corresponding to the lowest weighted average cycle time is the bottleneck, since reducing the total process time of this area has the largest impact.

The simulation will now permanently reduce the process time of the bottleneck area, and loop the same algorithm for a number of times. The user of the simulation determines how many times the simulation loops.

6.4 Process times

Within the four areas (infeed, rip cut, cross cut and stacking), there are separate processes that occur. These processes are depicted in the flowcharts of the logistics control in B PLC flowcharts in the appendix. It is tested whether the process times are dependent on the input. For some processes, it is indeed the case that it is dependent on the input stack type. For these processes, more data is gathered to determine what the relation between the processes and the inputs is. The results are given in *Table 6.2*. The steps taken, are explained more in detail in the appendix, in F Process time analysis description.

Processes	Constant (s)	Sheet thickness (mm)	Rip cuts	Cross cuts	Stack length (mm)	Stack width (mm)	Stack height (mm)	Sheets/parcel
1.1 Infeed pusher pushes group of sheets from stack	2.82							
1.2 Infeed pusher retraction	2.88							
1.3 Infeed nip rollers move group to parceling table	1.66							
1.4 Infeed scissor table moves up	-							
1.5 Infeed parcelling table moves down	1.92							
1.6 Infeed parceling aligner aligns parcel	5.89							

1.7 Infeed parceling table moves parcel to rip cut	13.53							
1.8 Infeed parceling table retreats	5.67							
1.9 Infeed scissor table (empty) moves down	19.57							
1.10 Infeed scissor table rolls in new stack	14.12							
1.11 Infeed scissor table (full) moves up	35.70						0.02	
2.1 Rip cut infeed table rolls in parcel	4.40							
2.2 Rip cut saw front cut	203.00	-0.20			0.00	-0.07		
2.3 Rip cut saw extra cut	151.40				0.00	-0.05		0.07
2.4 Rip cut saw back cut	185.50	-0.18	-2.36		0.00	-0.06		
2.5 Rip cut outfeed white belts moves parcel to cross cut	11.64							
2.6 Rip cut pusher retreats	11.17							
3.1 Cross cut saw front cut	229.20	-0.51			0.00	-0.08		
3.2 Cross cut saw extra cut	16.06			-0.38	0.00			
3.3 Cross cut saw back cut	38.92			-0.75				
3.4 Cross cut back cut delay before pusher retreats	20.35							
3.5 Cross cut outfeed rollers move parcel to stacking	27.32				0.00			
3.6 Cross cut pusher retreats	4.47				0.00			
4.1 Stacking parcel pusher pushes parcel on cookie tray	93.49	-0.06			0.00	-0.03		
4.2 Stacking parcel pusher retreats	22.76							
4.3 Stacking cookietray (full) moves parcel on scissor table/stack	58.41	-0.03				-0.01		
4.4 Stacking cookietray (empty) retreats	8.70							
4.5 Stacking scissor table (half full) moves down	4.96							
4.6 Stacking scissor table (full) moves down	197.10					-0.06	-0.03	
4.7 Stacking scissor table (empty) moves up	35.67							
4.8 Stacking outfeed rollers move stack to packing area	12.79				0.00			

Table 6.2: **Process times of all processes. When the process is not dependent on the input, it only has a constant, which is measured in seconds. When the process is dependent on the input, the factor that is in the table must be multiplied by the related property, on which the process time is dependent.**

6.5 Assumptions

Assumptions are made to develop the simulation. Simplifications are done because the real situation does not occur often, and it is estimated that it has only small effect on the results. See *Table 6.3* below for the list of assumptions.

Area	Assumption
General	The input of the last year is a good reference for the input of the future.
	The offcut is processed on time and does not cause a delay.
	The saw does not have to cut double offcuts.
Infeed	There is always a stack available on "Infeed Table 1".
	Every stack only has top and bottom coversheets, not in between.
	Coversheets always have a thickness of 15mm (same as "Parcel Setup_Manual", John Street Automation).
	A list of the variables when the coversheet pushes start and stop is provided by the operator of the B-saw.
	The synchronization of the infeed scissor table is negligible.
	When the coversheet pusher is initiated, the pusher only moves one sheet at a time.
	After the coversheet pushes of the premium sheets, all remaining premium sheets are moved in one push.
	The parcel is aligned every second push, and when the parcel is done.
Rip cut	All "extra" rip cuts (all rip cuts other than the first or last rip cut) within one input type have the same process time.
Cross cut	The trim pusher is always done before the front cross cut is done aligning.
	All "extra" cross cuts (all cross cuts other than the first or last cross cut) within one input type have the same process time.
Stacking	The stacking scissor table does not overshoot when it has a half full stack on it.

Table 6.3: **List of assumptions made to develop the simulation.**

6.6 Results & conclusion

The simulation is run for all different input types. For each input type, it calculates the cycle time. After all input types the weighted average cycle time is calculated, with the number of stacks as weight factor. The simulation now reduces each area by a second and calculates the weighted average cycle time. The area, for which the weighted average cycle time is the lowest, is considered the bottleneck. The process time of this area is decreased and the same procedure starts over. The results for 30 consecutive improvement runs are given below in *Table 6.4*.

Simulation number	Weighted average cycle time (min:sec)	Bottleneck	Improvement
0	08:10.2	Rip cut	0.0%
1	08:08.6	Back cross cut	0.3%
2	08:07.0	Rip cut	0.7%
3	08:05.4	Back cross cut	1.0%
4	08:03.8	Rip cut	1.3%

5	08:02.1	Rip cut	1.7%
6	08:00.4	Rip cut	2.0%
7	07:58.7	Rip cut	2.4%
8	07:57.0	Back cross cut	2.8%
9	07:55.4	Rip cut	3.1%
10	07:53.7	Rip cut	3.5%
11	07:52.2	Back cross cut	3.8%
12	07:50.6	Rip cut	4.2%
13	07:49.0	Rip cut	4.5%
14	07:47.5	Back cross cut	4.9%
15	07:46.1	Back cross cut	5.2%
16	07:44.7	Rip cut	5.5%
17	07:43.4	Back cross cut	5.8%
18	07:42.1	Rip cut	6.1%
19	07:40.8	Rip cut	6.4%
20	07:39.5	Rip cut	6.7%
21	07:38.2	Rip cut	7.0%
22	07:36.9	Rip cut	7.3%
23	07:35.6	Back cross cut	7.6%
24	07:34.4	Rip cut	7.9%
25	07:33.2	Back cross cut	8.2%
26	07:32.1	Rip cut	8.4%
27	07:31.0	Rip cut	8.7%
28	07:29.9	Back cross cut	9.0%
29	07:28.9	Infeed	9.2%
30	07:27.9		9.4%

Table 6.4: **Results of the simulation. Note that in row 30 only the result of reducing the bottleneck in row 29 is shown.**

As one can see, the rip cut area is the bottleneck 19 out of 30 times. It can be concluded that the rip cut area is the most important area to make improvements on the weighted average cycle time.

It may come as a surprise that the rip cut is the main bottleneck. This is, however, partly explained by the fact that a large part of the input of the B-saw has more rip cuts than cross cuts (40.6%). Next to that, the rip cut could also be the bottleneck when the number of rip cuts is equal to the number of cross cuts (40.7%).

Since it is expected that the rip cut is hard to improve, two other situations are considered. One is where the rip cut cannot be changed at all, the other where the rip cut area can be improved by no more than 8 seconds. The results are given in D Simulation results with restrictions in the appendix. For comparison, the results of the three situations are plotted in a graph, seen in *Figure 6.1*.

As can be seen, making no improvements on the rip cut at all, does not have dramatic effects on the weighted average cycle time. With an improvement of no more than 8 seconds on the rip cut, the weighted average cycle time does, however, still reduce significantly and is quite close to the result with no restrictions. This can be done by mainly reducing the "Back cross cut" (10 seconds) and the "Infeed" (11 seconds).

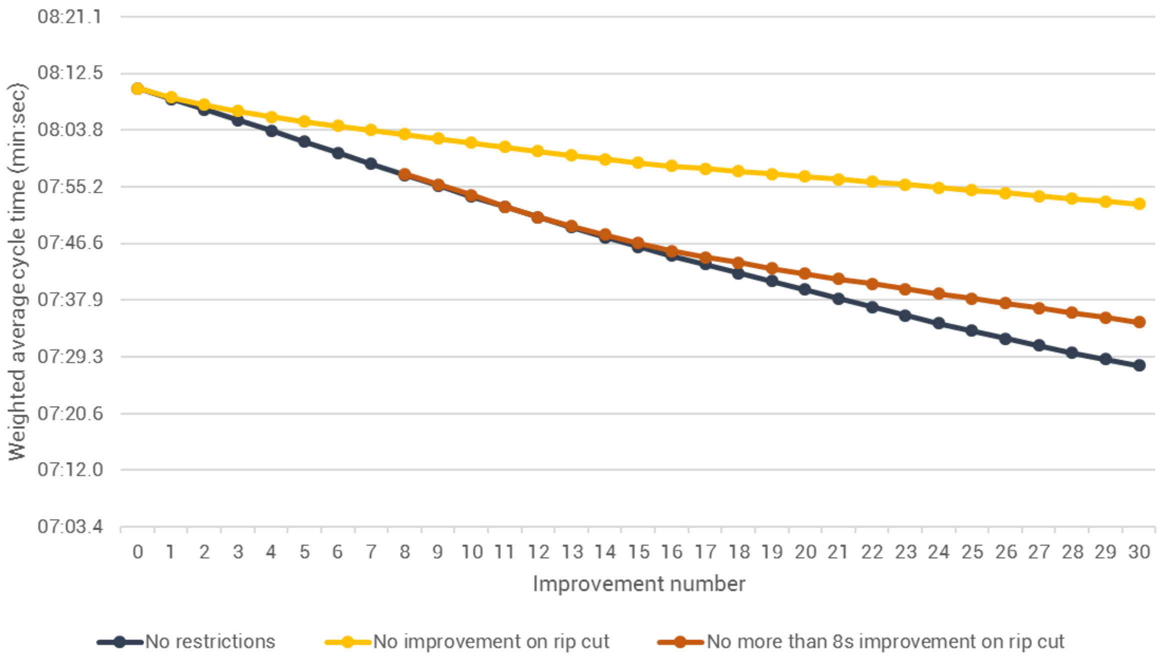


Figure 6.1: **Results of the simulation study of the B-saw. As one can see, the situation with no restrictions obviously is the best, and has an impact on the weighted average cycle time of 9.4%.**

Reducing the process time at the right place can have a significant effect on the total throughput. Since the rip cut is currently the bottleneck for a large part of the input stacks, reducing the process time of other areas does not have a big impact. Therefore, it is recommended to try to reduce the process time of the "Rip cut" area as much as possible. When no more improvements are possible, one should reduce the "Back cross cut" and the "Infeed". Also, see D Simulation results with restrictions in the appendix. The simulation can be used again, to see what areas should be reduced to gain further improvement.

Since the typical number of cross cuts is relatively high (2 - 6) compared to the rip cut (2 - 4), it is expected that the result of decreasing the rip cut process time, results in a higher variance of the cycle times of the packs going to the strapping line. This could result in the strapping line being too slow (holding up the B-saw), or too fast (waiting for input from the B-saw). Therefore, the effect of implementing the 30 second improvements on the pack cycle time is studied.

The cycle times of the packs in the current situation are compared with the 30 second improvements situation. The results are given below in *Figure 6.2* and *Table 6.5*.

Pack cycle time statistics (min:sec)	Current situation	Situation with 30 second improvements
Mean	02:25.46	02:15.90
Standard Deviation	00:44.78	00:41.93
Minimum	00:46.10	00:45.90
Maximum	05:21.77	04:57.63

Table 6.5: **Statistics of the pack cycle time.**

As can be seen, the standard deviation, or variance, decreases with implementing the 30 second

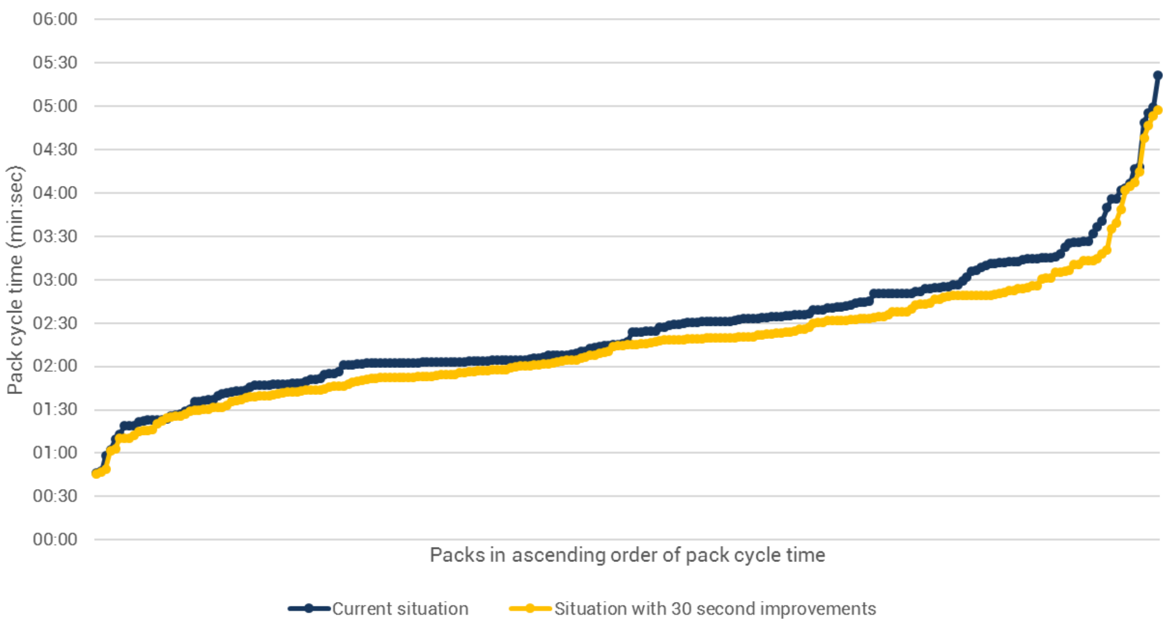
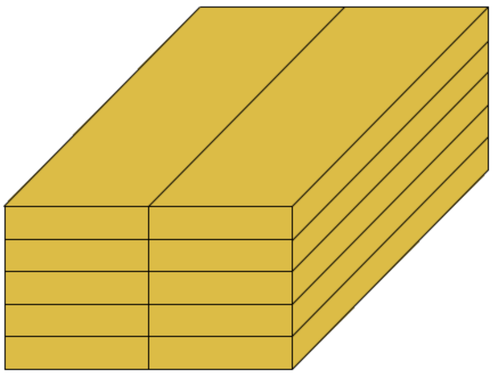


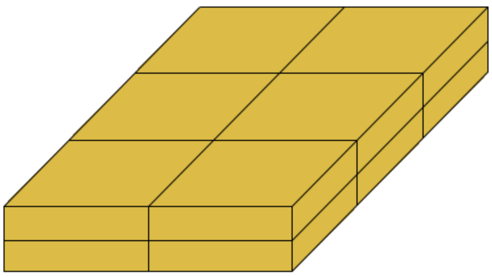
Figure 6.2: **Comparison of the pack cycle time in the current situation, and the situation where the 30 second improvements are implemented. In both situations, the cycle time is in ascending order, so the data points do not match to each other.**

improvements. The packs with a very high cycle time (displayed on the right in *Figure 6.2*), originate from stacks with a low number of packs per stack. See *Figure 6.3a* for an illustration of such a stack.

The packs with a low cycle time (displayed on the left in *Figure 6.2*), originate from stacks which have a high number of packs per stack, and have a low number of parcels per stack. See *Figure 6.3b* for an illustration of such a stack.



(a)



(b)

Figure 6.3: **(a) Example of a stack that has a high pack cycle time. This stack has 2 packs per stack and 5 parcels per stack. (b) Example of a stack that has a low pack cycle time. This stack has 6 packs per stack and 2 parcels per stack.**

It can be concluded that changing the process times of the B-saw does not have a significant effect on the cycle times of the packs going to the strapping line.

6.7 Validation

To research whether the simulation is reliable, a validation study is done. The cycle time, lead time (time from the start of a new stack, until that stack is done and moved to packing), and the process time for each area are measured. The simulation is run with the same input, after which the times are compared. See *Table 6.6* for the information about the stacks for which the process times were measured. Graphs of the comparison between the real situation and the simulation are given in *Figure 6.4*.

Test	Thick-ness (mm)	Stack length (mm)	Stack width (mm)	Rip cuts	Cross cuts	Sheets	Parcels
1	2.50	4290	2550	4	3	360	6
2	30.00	7400	2510	3	4	30	6
3	7.00	4050	2550	3	2	80	4
4	12.00	4200	2550	3	2	59	5
5	12.00	3770	2550	3	3	75	6
6	4.00	3570	2550	3	3	230	6
7	3.00	4210	2550	4	3	200	4

Table 6.6: **Stack information for which the process times were measured for the validation study.**

There is a limited number of comparisons of the cycle time and lead time, since these must be measured at a time when the B-saw is running without stopping.

The infeed shows a lot of variation. This is explained by the fact that the operator has a lot of influence on what happens at the infeed. It is tried to simulate the decisions the operator makes, but it is of course not fully accurate. It is assumed that it will only have a limited effect on the results of the simulation. This is, however, not validated.

The cross cut process times are lower in every situation. This is caused by the fact that the cross cut pusher retreats all the way to the back. Only in the case when the cross cut area is the bottleneck, and a parcel is waiting on the white belts, the cross cut pusher moves to the right position. In the simulation, however, it is assumed that the cross cut pusher moves to the right position in every situation, even when it is not the bottleneck. This does not have any effect on the cycle time, and only limited effect on the lead time, since the cross cut area was not the bottleneck in these situations.

In conclusion, the validation shows that for a range of input stacks, the model provides an accurate simulation of the B-saw.

6.8 Implementation

It was expected to be able to implement the results of the simulation during the internship. However, during the last weeks of the internship, the electrician who is able to change the PLC did not have time.

However, a ten second improvement possibility is identified at ”Back cross cut”. Some smaller improvement possibilities were identified at the ”Rip cut”. These possibilities are communicated with the electrician. It is expected that the simulation results will soon be implemented.

Figure 6.4: **Process time comparison between the B-saw and the simulation of the B-saw. The cycle time, lead time, infeed time, rip cut time, cross cut time and stacking time are compared.**

Chapter 7

Conclusions

This report started out with the goal of improving the sawing machines at Nelson Pine, to reduce the need for overtime. The overall equipment effectiveness was used as a framework. It was decided to focus on the machine with the highest downtime. This turned out to be the B-saw (with a downtime of 22%). The causes of the downtime of the B-saw were investigated, and a Pareto analysis was done on the causes. The top ten downtime reasons, which account for 40% of the downtime, were discussed with employees of Nelson Pine. To tackle the problems that were still relevant, the problems were divided over the employees.

An attempt was made to solve one of the major problems, the ”White belt broken”. Together with the relevant ”White belt off”, this problem accounts for 6% of the downtime. In the case the designed ”Infeed blocks” would work, it would not only reduce the downtime by solving the white belt problems, but also increase the quality of the boards (which is also a factor of the overall equipment effectiveness). Since the strapping line has to manually remove broken boards, a quality increase would lead to a lower downtime of the ”Strapping line down” (this problem currently accounts for 6% of the downtime).

Before this internship, it was only possible by observation to see whether these problems are indeed solved. To facilitate a culture of continuous improvement, an automatic downtime analysis system is implemented in the B-saw. Every time the machine stops for a consecutive time of two minutes, the operator must assign a downtime reason associated with the stop.

Next to the uptime and quality improvement stated above, the throughput, or theoretical output, of the B-saw was researched. This was done with the aid of a simulation model. The simulation model looked for the bottleneck area, and the bottleneck area that would appear when the process time of the previous bottleneck area would be reduced by one second. This was done for 30 times. Based on the simulation results, the B-saw can be improved by adjusting the programmable logic controller software. The improvements made with Nelson Pine, should result in an overall throughput improvement of almost 10%.

The improvement in throughput is amplified by a higher uptime, so this research leads to a direct increase in overall equipment effectiveness of the B-saw of about 16%.

Chapter 8

Recommendations

During the weekly ”Sanders and saws meetings”, currently, no information is given about the downtime of the sander and sawing machines. Only a subjective comment is given by the work supervisor whether there were any major issues last week. To create awareness of the significant amount of downtime at the sawing machines (potentially also at the sander machines), the writer recommends that the downtime of the last week of the B-saw will be inspected every week during the ”Sanders and saws meetings”. Major problems can be discussed shortly, after which action points could be given.

Next to the weekly analysis of downtime problems, it is recommended to inspect the downtime reasons over a longer period of time, say three months. Problems that are not significant during a week’s period of time, might have a big impact on a longer period of time when they are reoccurring frequently. Also, a comparison between different periods of time, might work very stimulating when it can be seen that problems are solved, and downtime decreases.

This way of working should result in a culture of continuous improvement. When the major problems are solved, the downtime should decrease, after which the maintenance staff is called less frequently. The maintenance staff should now have more time to focus on different machines, or on improving the uptime of the machine even further, by solving less significant problems.

It is advised to not implement the downtime system on other machines yet, but rather use the system on the B-saw only and prove its worth. In that case, supervisors and operators of other machines might see the added value of such a system and use it properly.

In case the downtime of one or multiple machines has been reduced significantly, and the machines should be able to process even more board, simulation studies can be done to further increase the capacity of the machines. The simulation made during this study, can be used to further improve the B-saw. New simulation studies can be made to analyze and improve other machines.

Appendix A. Infeed block results

	Original situation		Optimal 2 blocks (64 & 133mm)	
Length (mm)	Block (mm)	Cross cut rollers overhang (mm)	Block (mm)	Cross cut rollers overhang (mm)
3100	100	70	64	34
3150	50	70	64	84
3200	0	70	0	70
3560	0	86	0	86
3750	50	75	64	89
3770	0	45	0	45
3780	0	55	0	55
4050	0	80	133	33
4060	100	10	133	43
4100	100	50	64	14
4110	50	10	64	24
4150	50	50	64	64
4200	0	50	0	50
4210	0	60	0	60
4250	0	100	133	53
4280	100	50	133	83
4290	100	60	64	24
4350	50	70	64	84
4360	0	30	0	30
4460	0	130	133	23
4560	100	90	133	3
4760	0	70	0	70
4770	0	80	0	80
4800	0	110	133	3
4950	0	20	0	20
4960	0	30	0	30
4990	0	60	0	60
5160	50	40	64	54
5180	0	10	0	10
5200	0	30	0	30
5480	100	50	64	14
5555	0	25	0	25
5570	0	40	0	40

5800	0	35	0	35
6310	0	185	64	4
6560	0	70	0	70
6720	100	95	64	59
6970	0	5	0	5
7280	50	5	64	19
7400	50	5	64	19
7410	50	15	64	29
7460	0	15	0	15

Table A.1: **Table with the blocks that should be used for a certain length of an input stack. The results are given for the original situation, and the situation with 2 optimal blocks.**

Appendix B. PLC flowcharts

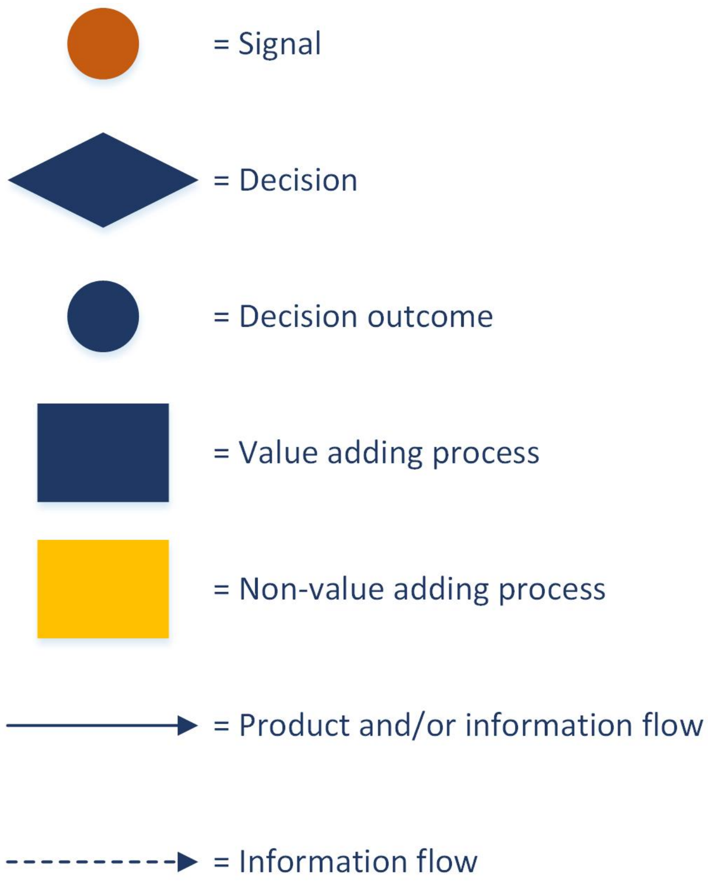


Figure B.1: **Legend for all PLC flowcharts.**

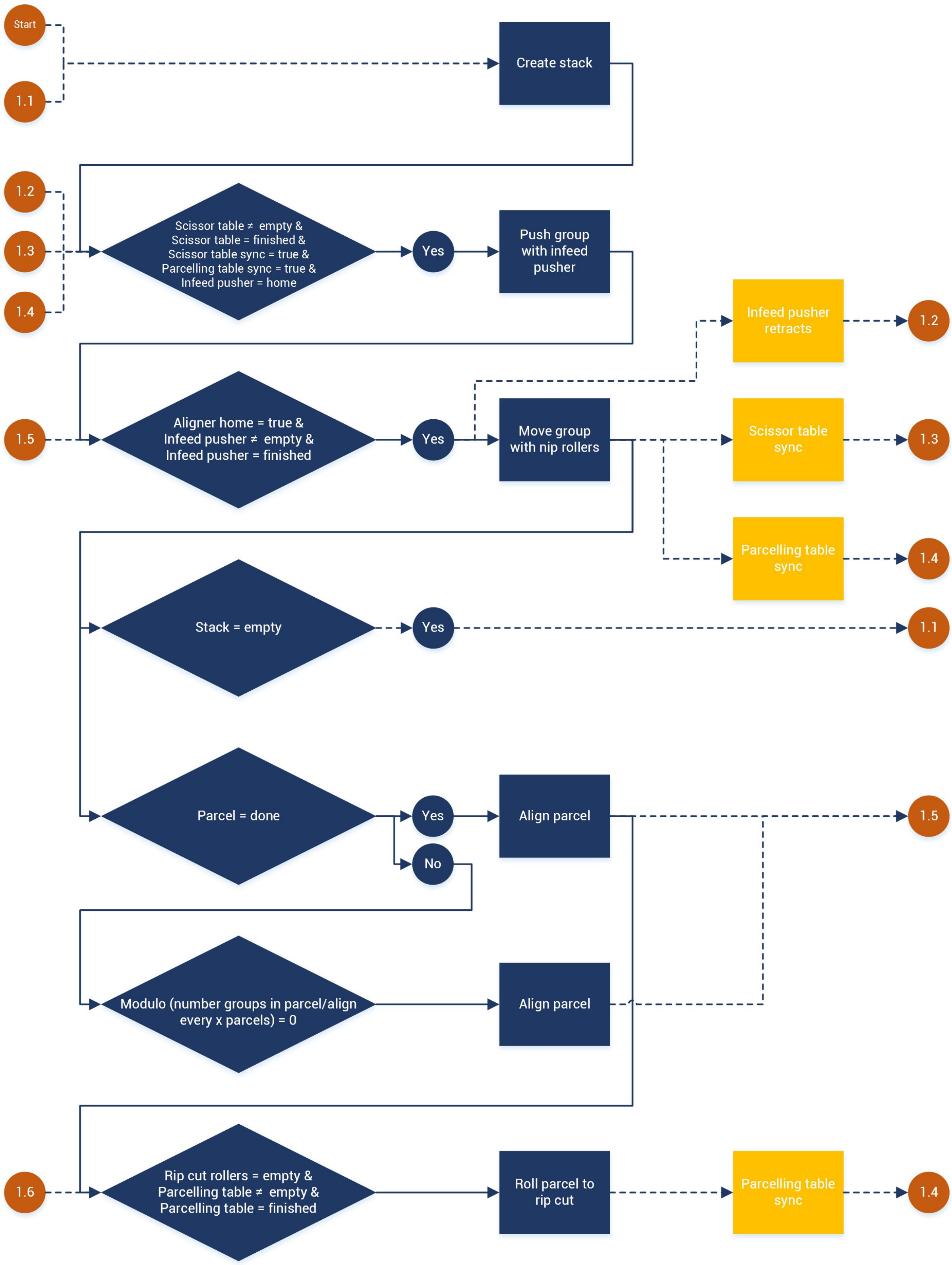


Figure B.2: **Flowchart of the PLC of the infeed area.**

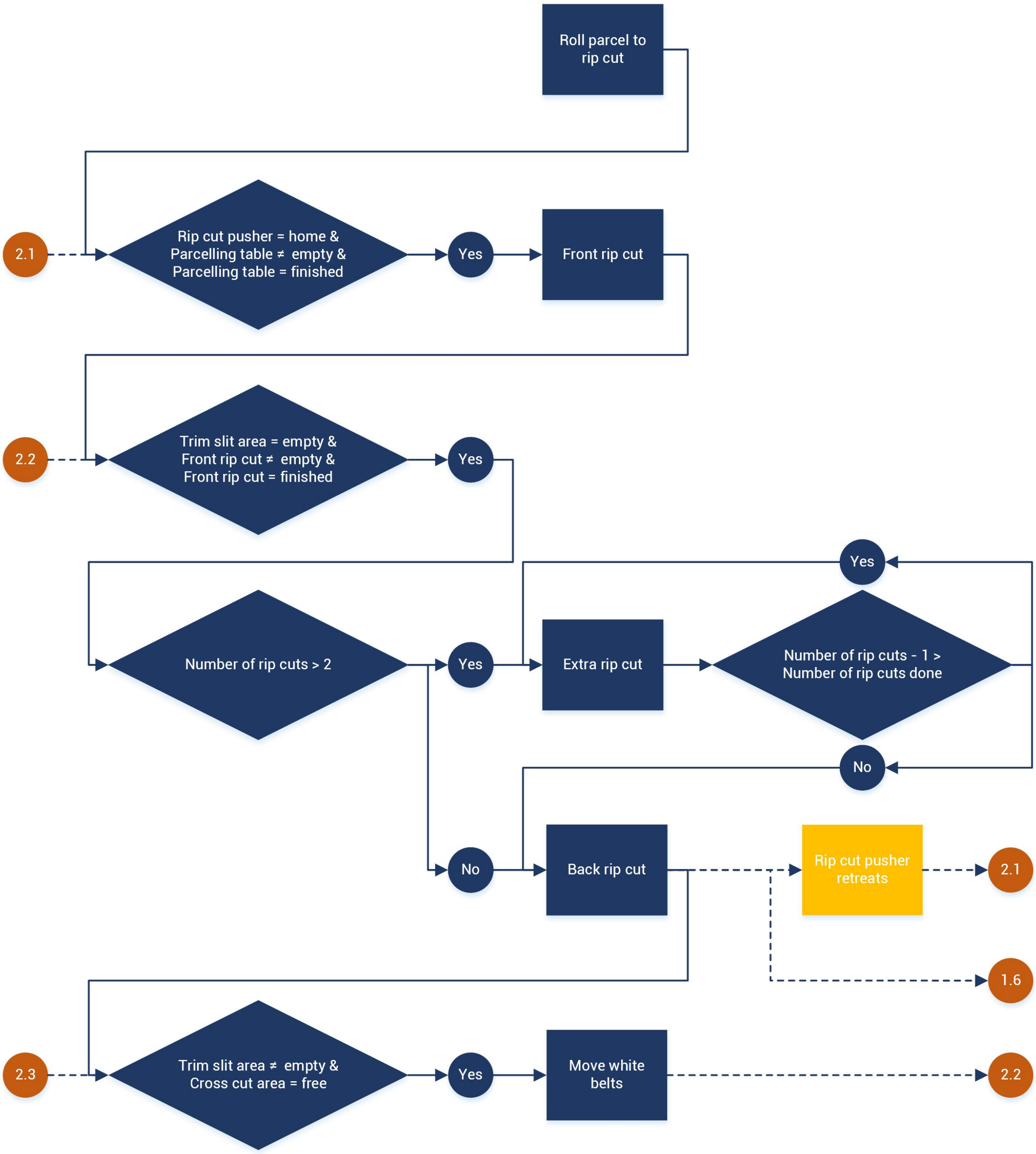


Figure B.3: **Flowchart of the PLC of the rip cut area.**

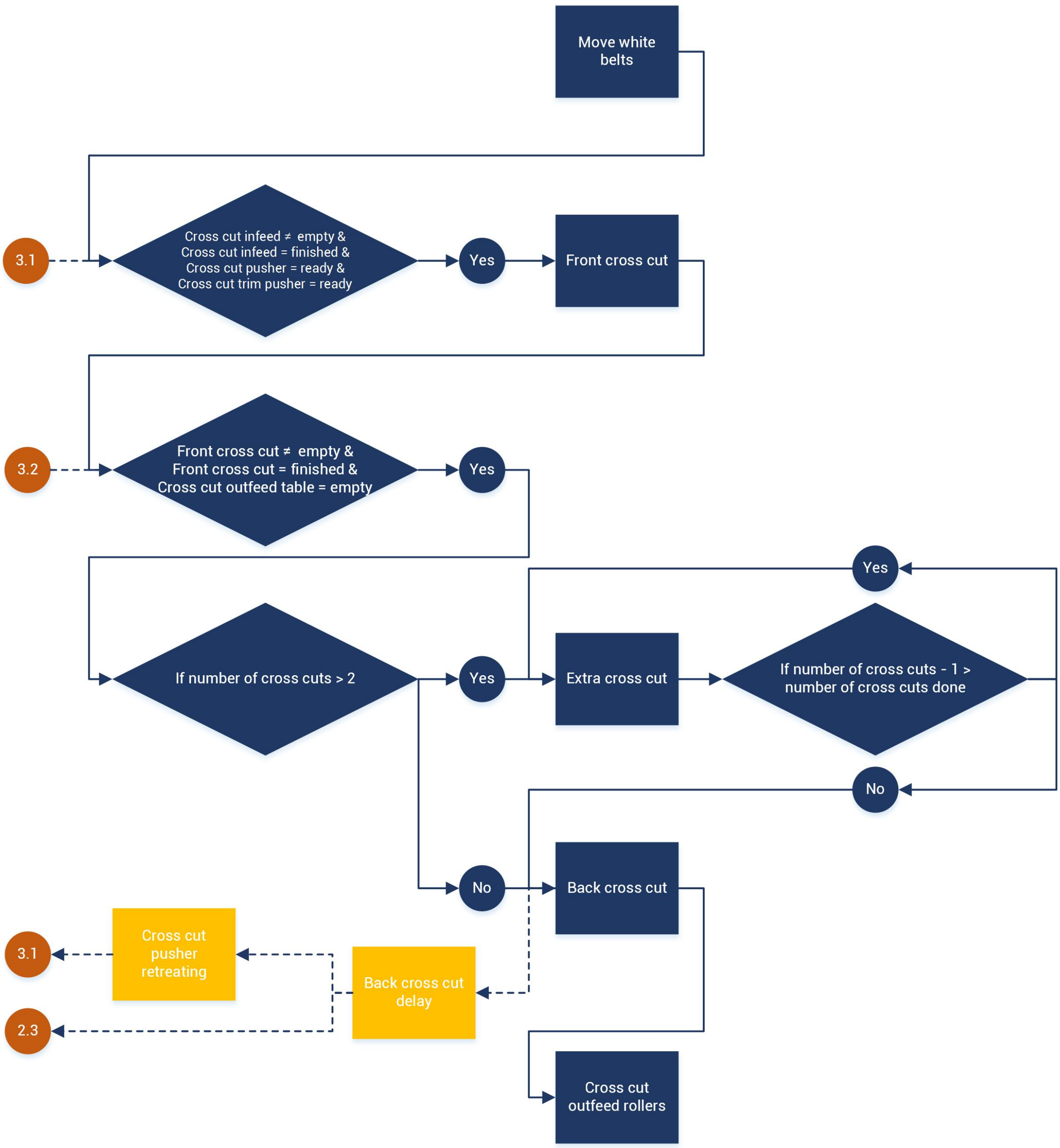


Figure B.4: **Flowchart of the PLC of the cross cut area.**

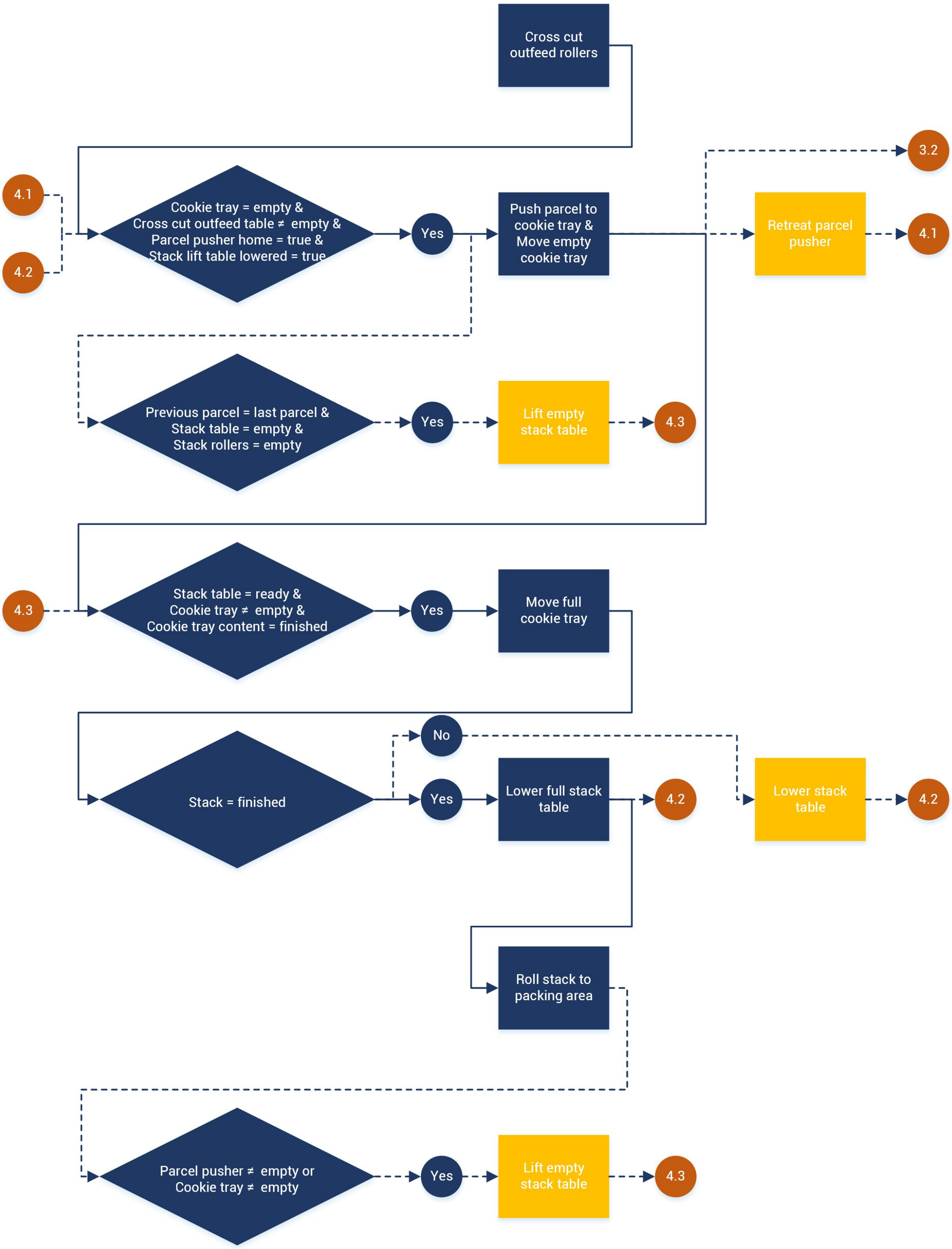


Figure B.5: **Flowchart of the PLC of the stacking area.**

Appendix C. Simulation model

The model is developed in Technomatix Plant Simulation 11. The model consists of a main screen, shown in *Figure C.1*, from which the simulation is controlled. One can change the variables seen in "Simulation control" to alter the simulation.

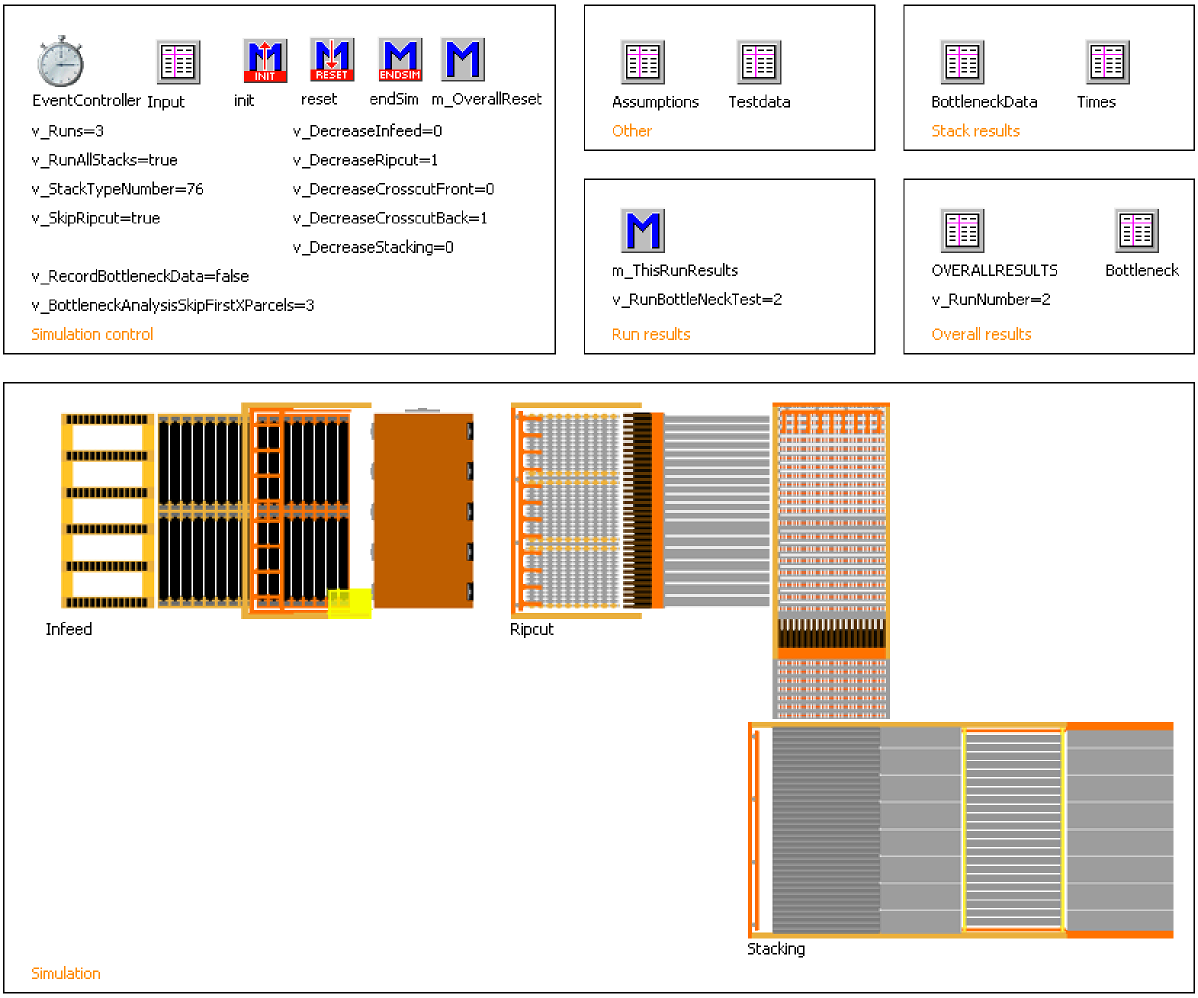


Figure C.1: **Main screen of the simulation. From here the simulation can be controlled. One can zoom in on the areas Infeed, Rip cut, Crosscut and Stacking.**

The exact way the simulation works, should be explained by the PLC flowcharts. However, the simulation will be explained shortly per area. Note that not all details of the simulation are considered. For more detail, the reader is referred to the simulation file.

C.1 Infeed

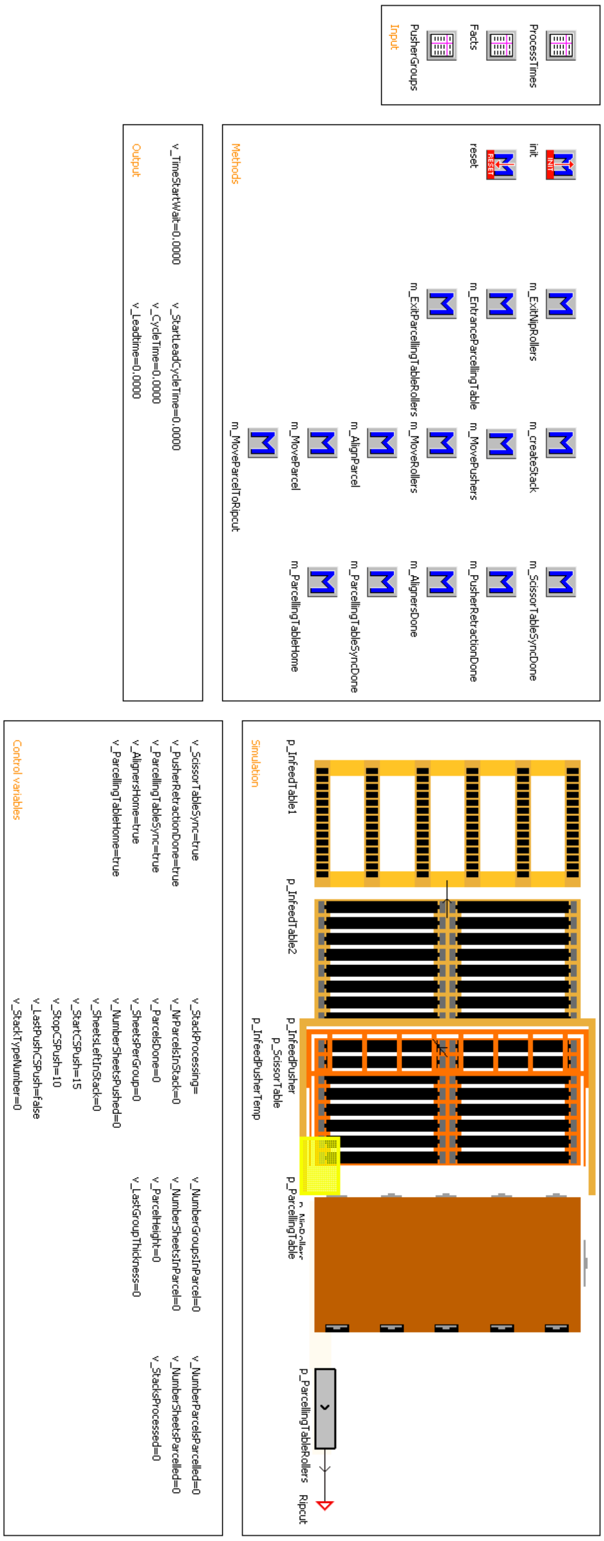


Figure C.2: **Infeed area of the simulation.**

The simulation screen of the infeed can be seen in *Figure C.2*. At the beginning of the simulation, a stack is created. This first stack incorporates the settings that are given in the main screen in the table “Input”. The stack first rolls on the scissor table and is lifted. Now the infeed pusher can push sheets, with a number of “v_SheetsPerGroup” sheets per push. The nip rollers move the sheets to the parceling table.

After two pushes, the parceling table aligners align the parcel, and does this for every second push. Beforehand, it is calculated how many pushes must be done for the first parcel and a standard (not first and not last) parcel in a stack. This calculation is done in Excel and is meant to simulate what the operator would do. After these number of pushes, the parcel is aligned again, after which it is moved to the rip cut area, assuming this area is free.

For the last parcel in a stack, the sheets are pushed until there are less than “v_StartCSPush” in the stack left. In that case, the infeed pusher starts to push sheets one by one, until there are less than “v_StopCSPush” left in the stack. It will now push all sheets, except the coversheet. The coversheet is the last push of the stack.

C.2 Rip cut

The simulation screen of the rip cut can be seen in *Figure C.3*. When the parcel arrives from infeed, and the cross cut pusher is in its home position (where it is located now), the front rip cut is started. After the front rip cut it is checked whether the rip cut outfeed area is free. If so, the second cut can start. The parcel has information from the “Input” table in the main screen, which says how many rip cuts must be done. If three or more rip cuts need to be done, it is sent to the extra rip cut. If not, it is sent to the back rip cut. After the back rip cut, and when the cross cut area is free, the parcel is moved to the cross cut area with the white belts.

C.3 Cross cut

The simulation screen of the cross cut can be seen in *Figure C.4*. At cross cut, the same principle applies as at the rip cut. Now, however, after the front cut, it is checked whether the cross cut outfeed area is free. If so, the second cut can start, in the same manner as the second rip cut.

C.4 Stacking

The simulation screen of the stacking can be seen in *Figure C.5*. When a parcel arrives at the cross cut outfeed table, the empty cookietray moves to the left (on top of the stacking scissor table) and the parcel is pushed on the cookietray. When the cookietray now moves back to the right, the parcel stacked on top of the other parcels (or on the scissor table when it is yet empty). When it was the last parcel (the parcel contains information whether it is the last parcel), the scissor table is lowered all the way, and the stack is rolled away towards the packing area.

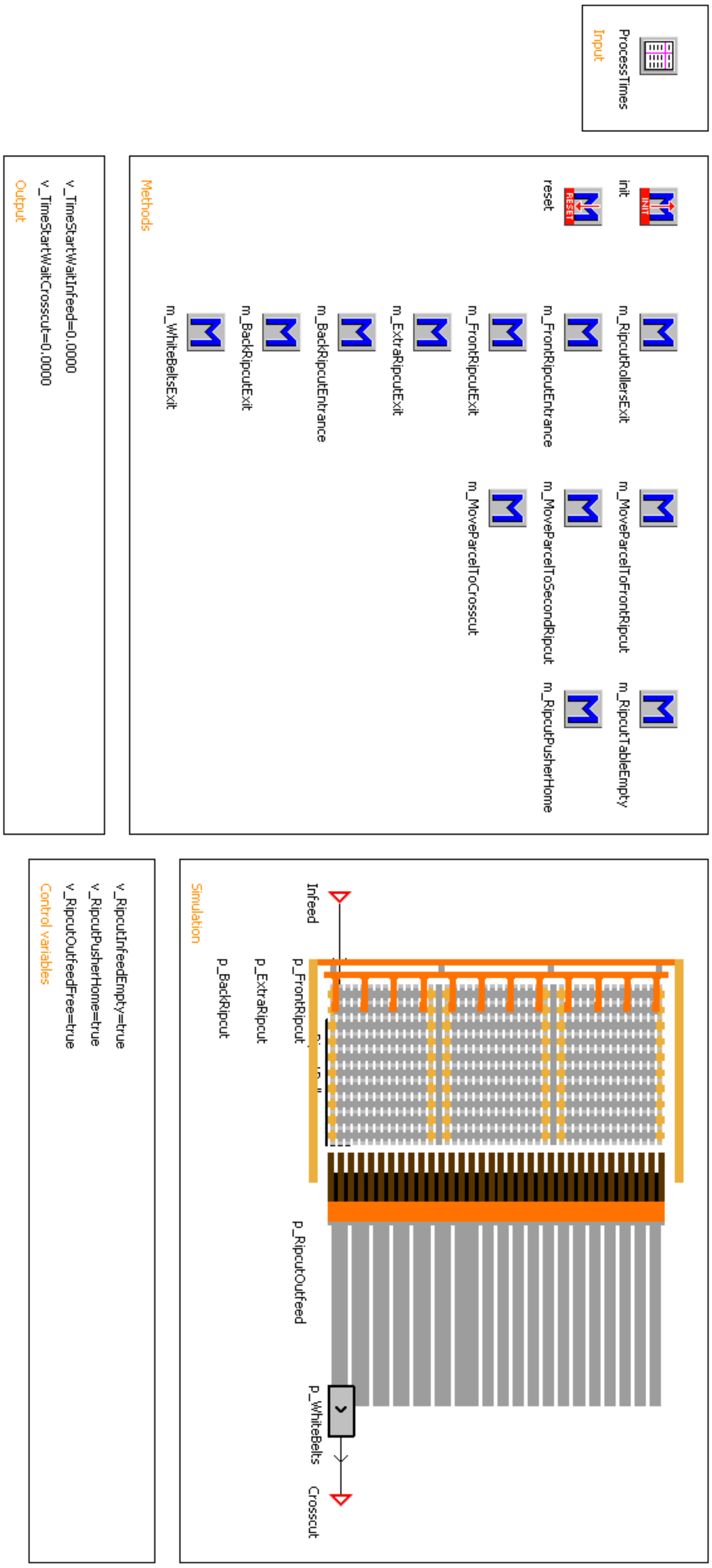


Figure C.3: **Rip cut area of the simulation.**

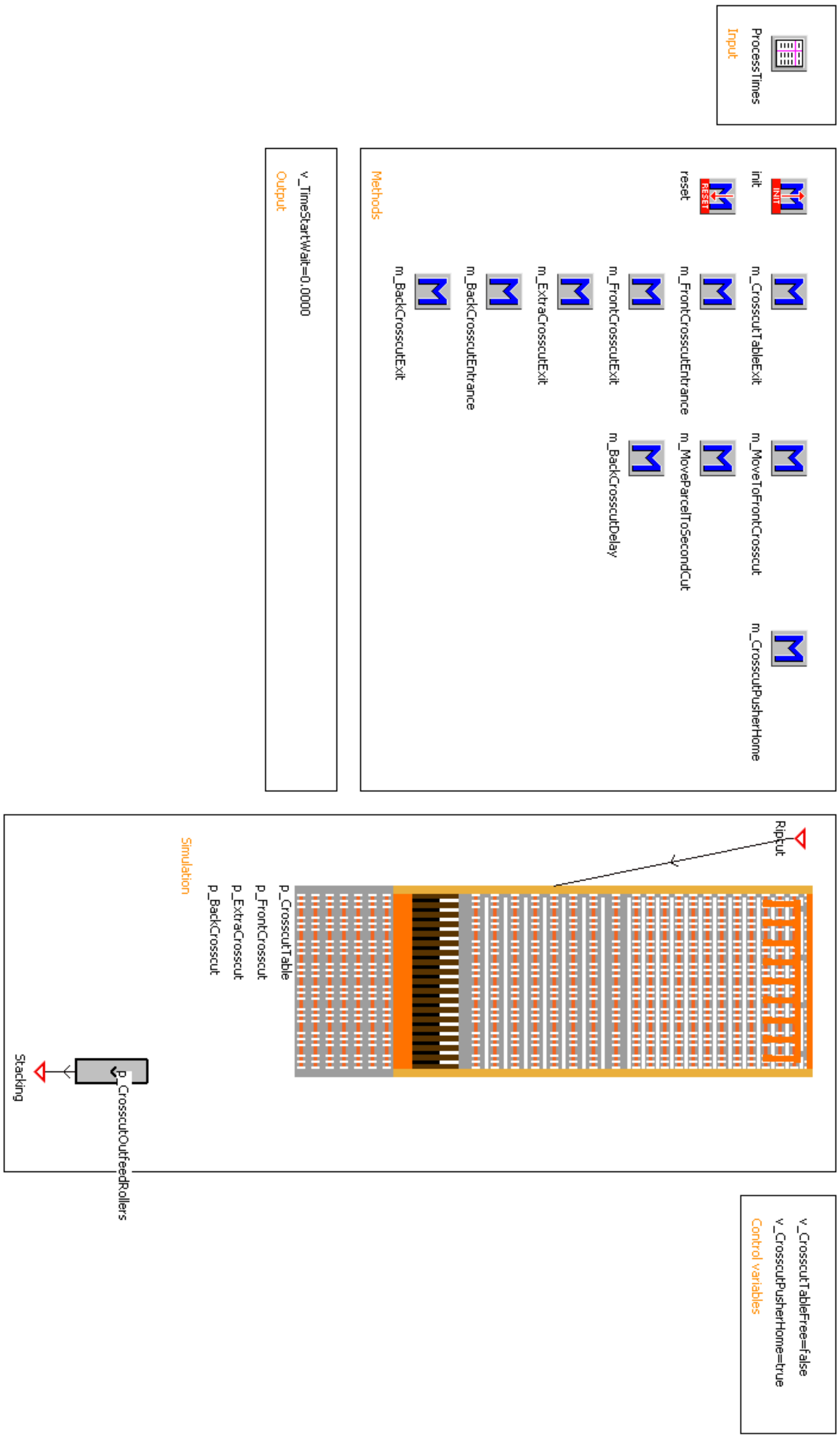


***Figure C.4:* Cross cut area of the simulation.**

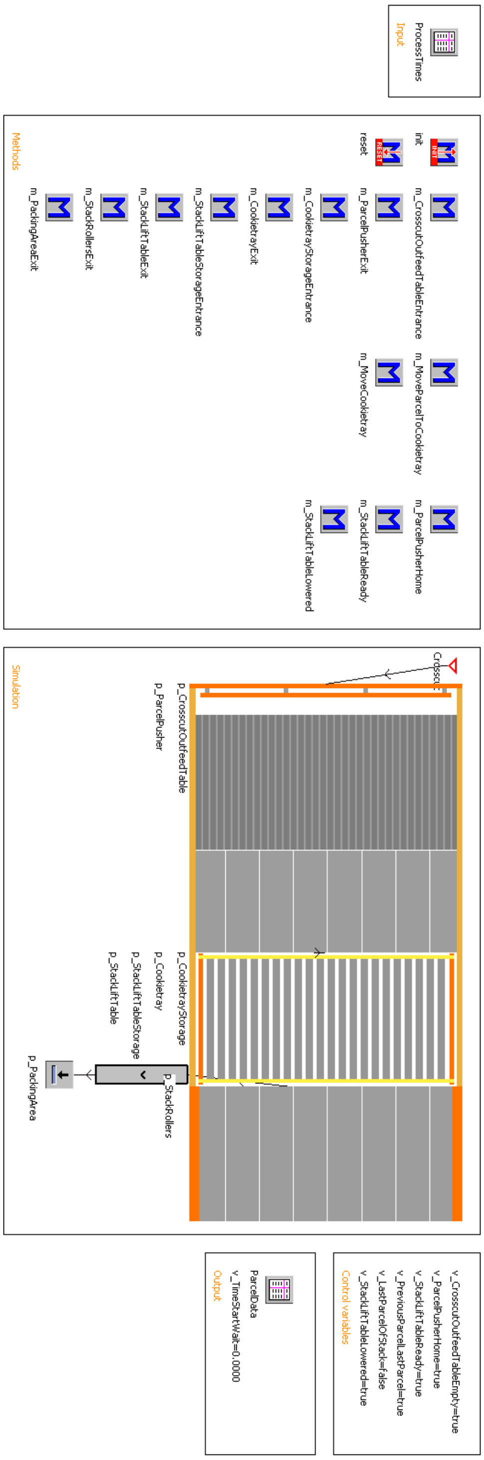


Figure C.5: **Stacking area of the simulation.**

Appendix D. Simulation results with restrictions

Simulation number	Weighted average cycle time	Bottleneck	Improvement
0	08:10.2	Back cross cut	0.0%
1	08:08.9	Back cross cut	0.3%
2	08:07.7	Back cross cut	0.5%
3	08:06.7	Back cross cut	0.7%
4	08:05.9	Back cross cut	0.9%
5	08:05.1	Back cross cut	1.1%
6	08:04.5	Infeed	1.2%
7	08:03.9	Infeed	1.3%
8	08:03.2	Infeed	1.5%
9	08:02.6	Infeed	1.6%
10	08:01.9	Infeed	1.7%
11	08:01.3	Infeed	1.9%
12	08:00.6	Infeed	2.0%
13	08:00.0	Infeed	2.1%
14	07:59.4	Back cross cut	2.3%
15	07:58.8	Back cross cut	2.4%
16	07:58.4	Back cross cut	2.5%
17	07:58.0	Front cross cut	2.6%
18	07:57.6	Back cross cut	2.7%
19	07:57.2	Front cross cut	2.7%
20	07:56.8	Back cross cut	2.8%
21	07:56.4	Front cross cut	2.9%
22	07:55.9	Back cross cut	3.0%
23	07:55.5	Front cross cut	3.1%
24	07:55.1	Back cross cut	3.2%
25	07:54.7	Front cross cut	3.3%
26	07:54.3	Back cross cut	3.4%
27	07:53.8	Front cross cut	3.5%
28	07:53.4	Back cross cut	3.6%
29	07:52.9	Front cross cut	3.7%
30	07:52.6		3.7%

Table D.1: **Results of the simulation with the restriction that the rip cut area cannot be changed. Note that in row 30 only the result of reducing the bottleneck in row 29 is shown.**

Simulation number	Weighted average cycle time	Bottleneck	Improvement
0			
1			
2			
3			
4			
5			
6			
7			
8	07:57.2	Back cross cut	2.7%
9	07:55.6	Back cross cut	3.1%
10	07:53.9	Back cross cut	3.4%
11	07:52.2	Back cross cut	3.8%
12	07:50.6	Back cross cut	4.2%
13	07:49.2	Back cross cut	4.5%
14	07:47.9	Back cross cut	4.8%
15	07:46.6	Back cross cut	5.1%
16	07:45.4	Back cross cut	5.3%
17	07:44.4	Infeed	5.6%
18	07:43.6	Infeed	5.7%
19	07:42.8	Infeed	5.9%
20	07:42.0	Infeed	6.1%
21	07:41.2	Front cross cut	6.3%
22	07:40.4	Back cross cut	6.5%
23	07:39.6	Infeed	6.7%
24	07:38.9	Infeed	6.8%
25	07:38.2	Infeed	7.0%
26	07:37.5	Infeed	7.2%
27	07:36.7	Infeed	7.3%
28	07:36.0	Infeed	7.5%
29	07:35.3	Infeed	7.7%
30	07:34.6		7.8%

Table D.2: **Results of the simulation with the restriction that the rip cut area at the start is reduced by 8 seconds. After this, the rip cut cannot be changed. Note that in row 30 only the result of reducing the bottleneck in row 29 is shown.**

Appendix E. Simulation input

Pack name	Thickness (mm)	Stack length (mm)	Stack width (mm)	Rip cuts	Cross cuts	Sheets	Parcels	Percentage	Cycle time (min:sec)
L1 4060 1225	7	4200	2550	3	2	87	4	6.2%	06:27.7
L1 2050 1230	2.7	4200	2550	3	3	142	3	5.3%	05:32.0
L1 3970 1225	7	4050	2550	3	2	80	4	5.0%	06:25.4
L3 4120 1225	30	4250	2550	3	2	20	4	5.0%	05:48.5
L1 3980 1225	7	4050	2550	3	2	80	4	4.2%	06:25.4
L3 4200 2440	18	4250	2550	2	2	20	3	3.3%	04:16.4
L1 2020 0870	2.5	4460	2550	2	6	82	2	1.9%	03:50.5
L1 2445 0920	2.5	4760	2550	2	6	208	4	1.7%	10:40.2
L1 1830 1225	2.5	3770	2550	3	3	160	3	1.7%	05:45.5
L1 3650 1225	7	3770	2550	3	2	80	4	1.6%	06:22.1
L3 4200 1225	27	4250	2550	3	2	20	4	1.6%	05:53.0
L3 2870 1245	15	5800	2550	3	3	60	6	1.3%	09:56.7
L3 3075 1245	18	6310	2550	3	3	50	6	1.2%	09:49.2
L3 4000 1225	27	4100	2510	3	2	20	4	1.2%	06:20.0
L1 2075 0810	2.5	4280	2550	4	3	168	3	1.1%	06:13.0
L1 2135 1225	2.5	4350	2510	3	3	360	6	1.1%	11:21.0
L3 2530 1225	21	5160	2510	3	3	43	6	1.1%	10:03.3
L3 4000 1225	21	4100	2510	3	2	30	4	1.1%	06:30.0
L1 2020 1240	2.5	4200	2550	3	3	360	6	1.0%	11:21.0
L1 2440 1220	6	4950	2510	3	3	116	5	1.0%	07:07.0
L1 1825 1225	4	3770	2550	3	3	215	6	0.9%	10:18.7
L1 2100 0730	2.5	4280	2550	4	3	118	2	0.9%	04:44.2
L3 4060 1240	24	4250	2550	3	2	25	4	0.9%	05:57.9
L1 4150 2440	6	4200	2550	2	2	40	2	0.9%	03:14.2
L1 4150 2440	4	4200	2550	2	2	60	2	0.9%	03:49.7
L1 2440 1220	12	4950	2510	3	3	75	6	0.8%	10:22.7
L1 2007 1240	2.7	4200	2550	3	3	330	6	0.8%	10:37.1
L3 3660 1220	18	7400	2510	3	3	35	4	0.8%	07:13.7
L1 2450 0915	2.7	4760	2550	2	6	330	6	0.8%	16:00.2

L1 2440 0820	12	4990	2550	4	3	75	6	0.7%	11:37.8
L3 3250 1225	24	6560	2550	3	3	22	4	0.7%	06:25.0
L1 2720 1225	2.5	3150	2510	3	2	299	5	0.7%	09:59.3
L1 1470 1220	5.5	4560	2510	3	4	160	6	0.7%	12:21.2
L2 2400 0400	18	4990	2510	4	3	50	6	0.7%	12:15.8
L1 1825 1225	12	3770	2550	3	3	75	6	0.7%	10:19.0
L1 1995 0820	4	4050	2550	4	3	144	4	0.7%	07:55.7
L1 3075 1245	6	3200	2550	3	2	115	5	0.7%	06:17.7
L1 2445 1225	2.5	4950	2510	3	3	300	5	0.6%	09:37.7
L3 2160 1225	18	6560	2550	3	4	50	6	0.6%	12:18.1
L1 2460 2100	6	4280	2550	2	3	84	3	0.6%	04:47.3
L3 4060 1220	5.5	4250	2550	3	2	105	4	0.6%	06:31.7
L1 2100 0810	2.5	4280	2550	4	3	360	6	0.6%	12:21.9
L1 2440 1220	3	4950	2510	3	3	242	5	0.6%	09:08.1
L1 2100 0810	2.7	4280	2550	4	3	329	6	0.6%	12:17.3
L3 3680 1225	18	7460	2550	3	3	35	4	0.6%	06:45.6
L3 2080 1240	24	6310	2550	3	4	38	6	0.6%	12:15.0
L1 4060 1220	5.5	4200	2550	3	2	105	4	0.6%	06:31.1
L1 4000 1225	4	4050	2550	3	2	180	5	0.6%	08:13.6
L3 1490 1220	12	6310	2550	3	5	76	6	0.6%	14:25.7
L3 2530 1225	24	5160	2510	3	3	38	6	0.5%	09:56.0
L1 2160 1225	12	4460	2550	3	3	75	6	0.5%	10:16.1
L3 2440 1220	16	7400	2510	3	4	56	6	0.5%	08:34.0
L1 2440 1220	4.75	4950	2510	3	3	172	5	0.5%	08:59.9
L1 1995 0770	4	4050	2550	4	3	144	4	0.5%	07:55.7
L2 1830 0920	2.5	5570	2510	3	4	360	6	0.5%	12:26.1
L1 2980 1225	2.5	3150	2510	3	2	300	5	0.5%	09:37.7
L1 2440 1220	2.5	4950	2510	3	3	345	6	0.5%	10:59.2
L3 3220 1225	30	6560	2550	3	3	20	4	0.5%	06:22.3
L1 3660 1220	12	3770	2550	3	2	52	4	0.5%	06:12.5
L2 2400 0300	18	4990	2510	4	3	50	6	0.5%	12:15.8
L1 2440 1220	4	4950	2510	3	3	186	5	0.5%	09:02.4
L1 3000 1225	4	3150	2510	3	2	190	5	0.5%	08:36.3
L3 1425 1220	24	5800	2550	3	5	38	6	0.4%	14:15.4
L1 2040 1225	2.7	4200	2550	3	3	330	6	0.4%	10:37.1
L3 2065 1225	24	6310	2550	3	4	38	6	0.4%	12:15.0
L1 1825 1225	7	3770	2550	3	3	130	6	0.4%	08:33.2
L3 2745 1220	18	5800	2550	3	3	50	6	0.4%	10:03.8
L3 2460 0815	15	7460	2550	4	4	60	6	0.4%	12:24.8
L1 2150 0810	2.5	4460	2550	4	3	360	6	0.4%	12:26.0
L1 2320 1230	2.5	4760	2550	3	3	359	6	0.4%	11:41.4
L2 3660 1830	16	3750	2510	2	2	24	3	0.4%	02:56.8
L1 1840 1245	2.5	3770	2550	3	3	359	6	0.4%	11:41.4
L3 2500 1230	30	5160	2510	3	3	30	6	0.4%	10:03.9
L3 2465 1550	6	6310	2550	2	5	112	4	0.4%	09:38.6
L3 4300 1225	27	4350	2510	3	2	20	4	0.4%	06:23.0
L1 2465 1245	3	4990	2550	3	3	274	5	0.4%	09:34.8
L1 2440 1225	2.7	4950	2510	3	3	250	4	0.4%	08:07.7

L2 2065 1850	24	4280	2510	2	3	21	4	0.4%	06:52.5
L1 1995 0720	4	4050	2550	4	3	144	4	0.4%	07:55.7
L3 3075 1245	6	6310	2550	3	3	110	4	0.4%	06:55.6
L1 4060 1225	12	4200	2550	3	2	59	5	0.4%	07:51.6
L3 2465 1245	6	7460	2550	3	4	138	5	0.4%	08:43.0
L3 3075 1245	12	6310	2550	3	3	74	6	0.3%	10:03.1
L1 1995 0770	3	4050	2550	4	3	300	6	0.3%	12:07.3
L3 2445 0925	15	5800	2550	2	7	60	6	0.3%	18:09.6
L3 2135 1225	24	6560	2550	3	4	38	6	0.3%	12:15.9
L2 1800 0300	18	5480	2510	4	4	50	6	0.3%	12:26.9
L3 2440 1830	15	7400	2510	2	5	41	4	0.3%	10:09.2
L1 1490 1220	12	4560	2510	3	4	76	6	0.3%	12:18.8
L1 2150 1620	2.5	4460	2550	3	3	360	6	0.3%	11:21.0
L1 1995 0720	3	4050	2550	4	3	300	6	0.3%	12:07.3
L1 2440 1830	6	3770	2550	2	3	100	4	0.3%	06:35.9
L1 2160 1245	4.75	4460	2550	3	3	200	6	0.3%	10:02.1
L1 2445 1225	12	4950	2510	3	3	75	6	0.3%	10:22.7
L3 2150 1225	24	6560	2550	3	4	38	6	0.3%	12:15.9
L3 2745 1220	12	5800	2550	3	3	75	6	0.3%	09:54.6
L2 1800 0400	18	5480	2510	4	4	50	6	0.3%	12:26.9
L1 1995 0820	3	4050	2550	4	3	299	6	0.3%	12:07.3
L1 1825 1225	5.5	3770	2550	3	3	160	6	0.3%	10:21.3
L1 1990 1225	2.5	4050	2550	3	3	358	6	0.3%	11:35.1
L1 2440 1830	4	3770	2550	2	3	149	4	0.3%	06:44.7
L1 1620 1225	2.5	4950	2510	3	4	360	6	0.3%	12:23.7
L1 2445 1225	4	4950	2510	3	3	229	6	0.3%	10:51.3
L1 1750 1225	5.5	3560	2550	3	3	160	6	0.3%	10:22.2
L3 4150 2440	6	4250	2550	2	2	40	2	0.3%	03:14.2
L2 2070 0920	24	4280	2510	3	3	30	5	0.2%	08:20.7
L1 2460 2100	8	4280	2550	2	3	65	4	0.2%	06:52.2
L3 2150 1225	30	6560	2550	3	4	30	6	0.2%	12:13.8
L2 3700 1850	24	3750	2510	2	2	21	4	0.2%	05:21.8
L1 2465 1550	5.5	4760	2550	2	4	120	4	0.2%	08:10.5
L3 2160 1240	24	6560	2550	3	4	32	5	0.2%	10:13.3
L2 2510 0920	24	5180	2510	3	3	30	5	0.2%	08:17.0
L1 1840 1225	2.5	3770	2550	3	3	357	6	0.2%	11:27.6
L1 1670 1225	4	3560	2550	3	3	230	6	0.2%	10:15.9
L1 2440 1220	11	4950	2510	3	3	84	6	0.2%	10:25.4
L1 2440 2060	3	4200	2550	2	3	150	3	0.2%	05:44.3
L3 2440 1220	18	7400	2510	3	4	50	6	0.2%	12:44.9
L1 2040 1225	2.5	4200	2550	3	3	358	6	0.2%	11:35.1
L3 2440 1830	18	7400	2510	2	5	35	4	0.2%	10:03.1
L1 2440 2135	2.5	4350	2510	2	3	180	3	0.2%	06:12.3
L1 2440 1830	15	3770	2550	2	3	41	4	0.2%	06:52.0
L3 2440 1220	4	7400	2510	3	4	230	6	0.2%	13:27.3
L3 1525 1220	15	6310	2550	3	5	61	6	0.2%	14:24.6
L3 1525 1220	18	6310	2550	3	5	51	6	0.2%	14:23.6
L3 2465 1550	17	6310	2550	2	5	40	5	0.2%	07:12.0

L1 2440 1220	7.5	4950	2510	3	3	119	6	0.2%	08:49.9
L2 2365 1850	24	4990	2510	2	3	21	4	0.2%	06:50.5
L1 2440 1830	2.5	3770	2550	2	3	215	4	0.2%	07:21.6
L1 2200 1225	5.5	4460	2550	3	3	160	6	0.1%	10:06.9
L3 3075 1245	25	6310	2550	3	3	36	6	0.1%	10:03.6
L3 2440 1220	15	7400	2510	3	4	59	6	0.1%	12:54.0
L3 2440 1220	12	7400	2510	3	4	74	6	0.1%	13:03.1
L1 2440 0935	4	4760	2550	2	6	150	4	0.1%	10:39.8
L3 1470 1220	5.5	6310	2550	3	5	152	5	0.1%	12:03.4
L3 2445 1225	30	7400	2510	3	4	30	6	0.1%	12:23.2
L1 1425 1220	12	4350	2510	3	4	78	6	0.1%	12:18.0
L3 2440 1220	4.75	7400	2510	3	4	190	6	0.1%	13:25.1
L1 2145 1225	4	4350	2510	3	3	230	6	0.1%	10:40.7
L3 2150 1225	21	6560	2550	3	4	43	6	0.1%	12:17.0
L3 2445 1225	24	7400	2510	3	4	38	6	0.1%	12:26.7
L1 2440 0935	3	4760	2550	2	6	200	4	0.1%	10:40.0
L2 2720 0925	2.5	5555	2510	3	3	300	5	0.1%	09:37.7
L1 2440 1830	12	3770	2550	2	3	50	4	0.1%	06:52.7
L2 3660 1830	18	3750	2510	2	2	26	3	0.1%	04:55.7
L3 2440 1220	6	7400	2510	3	4	116	5	0.1%	08:54.2
L3 2135 1225	30	6560	2550	3	4	30	6	0.1%	12:13.8
L1 2300 1225	2.7	4760	2550	3	3	330	6	0.1%	10:37.1
L1 2440 1220	5.5	4950	2510	3	3	158	6	0.1%	10:42.9
L3 2745 1220	4.75	5800	2550	3	3	125	4	0.1%	06:52.4
L1 1425 1220	15	4350	2510	3	4	61	6	0.1%	12:17.0
L3 1425 1220	15	5800	2550	3	5	61	6	0.1%	14:18.6
L1 2030 1240	2.5	4200	2550	3	3	360	6	0.1%	11:21.0
L1 1970 1225	3	4050	2550	3	3	300	6	0.1%	10:11.2
L1 2135 1225	3	4350	2510	3	3	297	6	0.1%	10:47.9
L3 3075 1245	6.35	6310	2550	3	3	105	5	0.1%	06:53.2
L3 3660 1220	25	7400	2510	3	3	20	4	0.1%	07:01.9
L1 1525 1220	12	4760	2550	3	4	78	6	0.1%	12:13.4
L3 2745 1220	30	5800	2550	3	3	30	6	0.1%	10:04.0
L1 2445 1225	3	4950	2510	3	3	300	6	0.1%	10:58.5
L1 2150 1225	2.5	4460	2550	3	3	360	6	0.1%	11:21.0
L1 2465 1840	3	3770	2550	2	3	188	4	0.1%	07:13.4
L3 2135 1225	15	6560	2550	3	4	60	6	0.1%	12:19.1
L1 2135 1225	2.7	4350	2510	3	3	327	6	0.1%	10:44.8
L1 3660 1220	6	3770	2550	3	2	99	4	0.1%	06:25.0
L1 2445 1080	2.5	4460	2550	2	5	354	6	0.1%	14:07.3
L3 2440 1220	30	7400	2510	3	4	30	6	0.1%	12:23.2
L1 2440 1220	7	4950	2510	3	3	138	6	0.1%	08:51.9
L2 1990 0925	2.5	4110	2510	3	3	360	6	0.1%	11:21.0
L3 2445 1225	18	7400	2510	3	4	50	6	0.1%	12:44.9
L3 2800 0840	18	5800	2550	4	3	25	3	0.1%	05:49.2
L3 2440 1370	17	6970	2550	2	6	48	5	0.1%	08:19.5
L3 3660 1220	12	7400	2510	3	3	52	4	0.1%	07:23.9
L1 2130 1225	7	4350	2510	3	3	130	6	0.1%	08:42.7

L3 2440 1830	25	7400	2510	2	5	20	4	0.1%	09:49.0
L1 2200 1225	3	4460	2550	3	3	300	6	0.1%	10:11.2
L1 2445 1225	5.5	4950	2510	3	3	160	6	0.1%	10:43.4
L1 2430 1240	2.5	4990	2550	3	3	360	6	0.1%	11:21.0
L1 2445 0915	3	4760	2550	2	6	300	6	0.1%	16:00.1
L3 3400 1225	15	6970	2550	3	3	40	4	0.1%	06:44.7
L1 2440 1220	2.7	4950	2510	3	3	330	6	0.1%	11:01.2
L3 2440 1220	24	7400	2510	3	4	38	6	0.1%	12:26.7
L3 3660 1220	16	7400	2510	3	3	38	4	0.1%	05:27.7
L3 2440 0820	12	7460	2550	4	4	75	6	0.1%	12:34.1
L3 1525 1220	21	6310	2550	3	5	44	6	0.1%	14:22.5
L3 1730 1225	30	7280	2510	3	5	30	6	0.1%	14:36.9
L3 2070 1225	21	6310	2550	3	4	43	6	0.1%	12:16.0
L3 2465 1550	18	6310	2550	2	5	38	4	0.1%	09:35.7
L1 2465 1245	5.5	4990	2550	3	3	158	6	0.1%	10:00.5
L1 2465 1550	3	4760	2550	2	4	215	4	0.1%	07:33.0
L1 1825 1225	3	3770	2550	3	3	300	6	0.1%	10:11.2
L2 2445 0925	2.5	4990	2510	3	3	360	6	0.1%	11:21.0
L2 3660 1220	18	3750	2510	3	2	33	4	0.1%	06:30.5
L2 2400 0600	18	4990	2510	4	3	49	6	0.1%	12:15.8
L3 2465 1245	21	7460	2550	3	4	43	6	0.1%	12:20.4
L3 2460 1230	15	7460	2550	3	4	60	6	0.0%	12:37.3
L3 2745 1220	25	5800	2550	3	3	36	6	0.0%	10:05.7
L3 4060 1225	12	4250	2550	3	2	56	5	0.0%	07:52.0
L3 1425 1220	12	5800	2550	3	5	78	6	0.0%	14:19.7
L3 2160 1225	12	6560	2550	3	4	75	6	0.0%	12:20.2
L1 2465 1245	6	4990	2550	3	3	145	6	0.0%	08:18.8
L3 2440 1220	5.5	7400	2510	3	4	159	6	0.0%	13:22.8
L1 2400 1200	12	4950	2510	3	3	67	6	0.0%	10:21.9
L3 2440 1220	7	7400	2510	3	4	130	6	0.0%	11:05.2
L3 2465 1840	17	7460	2550	2	5	34	4	0.0%	07:25.7
L1 2465 1245	12	4990	2550	3	3	71	6	0.0%	10:12.8
L1 2440 0820	2.7	4990	2550	4	3	330	6	0.0%	12:33.5
L3 5130 1220	30	5200	2510	3	2	8	2	0.0%	03:14.1
L3 2745 1220	16	5800	2550	3	3	54	6	0.0%	04:52.6
L3 2450 1240	27	7460	2550	3	4	24	4	0.0%	08:12.2
L3 3060 1240	27	6310	2550	3	3	24	4	0.0%	06:22.8
L3 4940 1220	6	4990	2550	3	2	40	2	0.0%	03:14.2
L3 2440 2060	3	6310	2550	2	4	150	3	0.0%	05:44.3
L1 3075 1245	3	3200	2550	3	2	228	4	0.0%	08:06.3
L3 2440 1220	2.5	7400	2510	3	4	360	6	0.0%	13:31.9
L1 3660 1220	4.75	3770	2550	3	2	128	4	0.0%	06:28.8
L2 1800 0600	18	5480	2510	4	4	48	5	0.0%	10:23.8
L1 1525 1220	15	4760	2550	3	4	57	6	0.0%	12:12.3
L1 2400 1200	6	4950	2510	3	3	100	4	0.0%	07:07.6
L3 3660 1220	6	7400	2510	3	3	100	4	0.0%	07:36.4
L3 3660 1220	4.75	7400	2510	3	3	128	4	0.0%	07:40.2
L3 2160 1240	18	6560	2550	3	4	50	6	0.0%	12:18.1

L1 2465 1245	2.5	4990	2550	3	3	330	5	0.0%	10:16.6
L3 4060 1240	30	4250	2550	3	2	20	4	0.0%	05:48.5
L3 2440 1220	25	7400	2510	3	4	35	6	0.0%	12:24.9
L3 2445 1225	21	7400	2510	3	4	43	6	0.0%	12:35.8
L3 2150 1225	27	6560	2550	3	4	34	6	0.0%	12:14.9
L3 2465 1245	18	7460	2550	3	4	50	6	0.0%	12:28.2
L1 1830 1220	2.5	3770	2550	3	3	360	6	0.0%	11:21.0
L2 4060 0920	24	4280	2510	3	2	30	5	0.0%	08:03.8

Table E.1: **List of the input of the last year with the relevant information, sorted on percentage of total number of stacks. Twelve rows were deleted from this list, since it was unknown which stack was related to the pack. The cycle time is measured of the current situation, without changing any of the process times.**

Appendix F. Process time analysis description

The duration of each process is measured several times with a stopwatch. This is done for two different input stack types. By comparing the times of each process for the different inputs, it can be determined whether the process time is dependent on the input. This is tested with a Two Sample-T test, in Minitab. The results of the test are given in *Table F.1*.

Process	N	Mean	StDev	P value	Input dependent	Average (s)	Comment
1.1 Infeed pusher pushes group of sheets from stack	10	2.76	0.12	0.025	Yes	2.82	Together with Nelson Pine this will not be researched further.
	10	2.89	0.11				
1.2 Infeed pusher retraction	10	2.77	0.20	0.024	Yes	2.88	Together with Nelson Pine this will not be researched further.
	10	2.98	0.17				
1.3 Infeed nip rollers move group to parceling table	10	1.65	0.12	0.716	No	1.66	
	10	1.67	0.11				
1.4 Infeed scissor table moves up							Since it takes such a short time for the scissor table to move up, it is decided not to research this. This has no effect on the simulation results.

1.5 Infeed parceling table moves down	10	1.92	0.29	0.922	No	1.92	
	10	1.93	0.19				
1.6 Infeed parceling aligner aligns parcel	10	5.89	0.16	0.944	No	5.89	
	10	5.89	0.16				
1.7 Infeed parceling table moves parcel to rip cut	10	13.77	0.20	0.155	No	13.53	
	6	13.30	0.67				
1.8 Infeed parceling table retreats	10	8.63	1.67	0	No	5.67	The infeed parceling table was changed during the research, new data is used.
	5	10.25	0.19				
1.9 Infeed scissor table (empty) moves down	4	19.57	0.11	0.974	No	19.57	
	2	19.57	0.25				
1.10 Infeed scissor table rolls in new stack	4	15.00	2.93	0.328	No	14.12	
	2	13.25	0.47				
1.11 Infeed scissor table (full) moves up	4	11.73	0.44	0	Yes		
	3	18.70	0.39				
2.1 Rip cut infeed table rolls in parcel	11	4.36	0.20	0.159	No	4.40	
	5	4.45	0.03				
2.2 Rip cut saw front cut	14	35.19	1.38	0	Yes		
	15	33.22	0.49				
2.3 Rip cut saw extra cut	12	23.38	0.36	0	Yes		
	10	22.00	0.53				
2.4 Rip cut saw back cut	11	32.80	0.29	0	Yes		
	12	30.72	0.33				
2.5 Rip cut outfeed white belts moves parcel to cross cut	10	11.91	0.11	0	Yes		
	13	11.37	0.26				

2.6 Rip cut pusher retreats	9	11.05	0.32	0.047	No	11.17	
	10	11.30	0.09				
3.1 Cross cut saw front cut	6	46.14	8.14	0.138	Yes		
	8	40.27	0.32				
3.2 Cross cut saw extra cut	6	20.44	1.02	0.003	Yes		
	7	22.65	0.11				
3.3 Cross cut saw back cut	6	37.23	1.18	0.044	Yes		
	6	35.92	0.22				
3.4 Back cross cut cut delay before pusher retreats	10	20.69	0.27	0	Yes	20.35	Together with Nelson Pine this will not be researched further.
	12	20.02	0.25				
3.5 Cross cut outfeed rollers move parcel to stacking	5	16.94	0.33	0	Yes		
	6	12.52	0.12				
3.6 Cross cut pusher retreats	6	12.68	2.18	0.647	Yes		
	7	13.11	0.06				
4.1 Stacking parcel pusher pushes parcel on cookie tray	9	30.22	0.39	0	Yes		
	5	28.62	0.10				
4.2 Stacking parcel pusher retreats	5	22.73	0.16	0.414	No	22.76	
	5	22.80	0.08				
4.3 Stacking cookietray (full) moves parcel on scissor table/stack	13	24.38	0.14	0	Yes		
	5	24.00	0.05				
4.4 Stacking cookietray (empty) retreats	5	8.89	0.13	0.001	Yes	8.70	Together with Nelson Pine this will not be researched further.
	6	8.51	0.12				

4.5 Stacking scissor table (half full) moves down	7	7.78	3.58	0.87	No	4.96	Later in the internship it was noted that the scissor table regularly overshoots. For the simulation, it is assumed that the scissor table will never overshoot. New data is used.
	5	8.18	4.34				
4.6 Stacking scissor table (full) moves down	4	14.48	7.76	0.509	No		Not looking at the p value, the data suggest that there is variation, so this is researched further.
	3	11.56	0.70				
4.7 Stacking scissor table (empty) moves up	3	35.69	0.38	0.872	No	35.67	
	3	35.64	0.16				
4.8 Stacking outfeed rollers move stack to packing area	2	44.20	0.05	0.001	Yes		
	3	31.72	0.61				

Table F.1: **Process list with the results of the two sample t-test. For the processes that are not dependent on the input, the average is given.**

A p-value of 0.050 or lower, generally means that the process time is dependent on the input. However, the p-value is only used as an indication. Together with Nelson Pine it was in some cases decided not to do a research on the dependency. This was done in cases where the mean did not differ much or the reason behind the difference was suspected and the dependency would probably not have a significant effect on the results of the simulation.

More data is collected for the processes which are dependent on the input and for which it was decided to research further what the dependency on the input is. This data is evaluated with the "Fit Regression Model" function in Minitab. For the number of input variables, at least eight measure points are required. For each measurement point, multiple measurements are done to get a better average.

The method of determining the effect of the input on the process time is explained by showing the method steps for "4.8 Stacking outfeed rollers move stack to packing area". The measurement values, together with the input variables, for process "4.8 Stacking outfeed rollers move stack to packing area" are given in *Table F.2*.

Sheet thickness (mm)	Sheets/stack	Stack length (mm)	Stack width (mm)	Stack height (mm)	Rip cuts	Cross cuts	Parcels/stack	N	Average time (s)
18	50	7400	2510	900	3	4	6	2	44.20
12	75	4460	2550	900	3	3	6	3	31.72
5.5	104	4200	2550	572	3	2	4	5	30.17
2.7	330	4210	2550	891	3	3	6	3	30.30
6	112	6310	2550	672	2	5	5	3	40.60
9	100	6310	2550	900	3	3	6	3	39.90
9	78	4290	2550	702	3	2	5	3	30.04
18	35	7460	2550	630	3	3	4	2	42.22

Table F.2: **Measurement values for "4.8 Stacking outfeed rollers move stack to packing area". This data is used as input for the Fit Regression Model in Minitab.**

The results of the Fit Regression Model are given in *Figure F.1*. As can be noted, the sheet thickness and sheets/stack are not incorporated as variables. The reason for this is that these two variables result in the height. According to Brook [2014], when a variable is dependent on another variable, only one of them should be included.

```
Coefficients

Term                 Coef    SE Coef  T-Value  P-Value      VIF
Constant              566        506     1,12    0,464
Ripcuts             -26,5       23,8    -1,12    0,465   725,55
Crosscuts           -7,03       6,65    -1,06    0,483   445,85
Length (mm)      0,004014   0,000481     8,34    0,076     4,95
Width (mm)         -0,183      0,167    -1,10    0,471    57,00
Height (mm)         0,113      0,115     0,99    0,504  2678,16
Parcels/stack       -14,5       15,5    -0,93    0,522  1930,98


Regression Equation

Average = 566 - 26,5 Ripcuts - 7,03 Crosscuts + 0,004014 Length (mm) - 0,183 Width (mm)
          + 0,113 Height (mm) - 14,5 Parcels/stack
```

Figure F.1: **Result of Minitab's Fit Regression Model for "4.8 Roll stack away" with all variables. The p-value indicates the dependency on the process time.**

The results of the Fit Regression Model are given below in *Figure F.2*. As can be noted, the sheet thickness and sheets/stack are not incorporated as variables. The reason for this is that these two variables result in the height. According to Brook [2014], when a variable is dependent on another variable, only one of them should be included.

To check the regression model on correctness, the residuals are inspected. The residuals seem normally distributed (top left and bottom left), have random spread over the fitted value (top right graph), are fairly normal distributed (bottom left graph) and the residuals follow a random path along the observation order (bottom right graph). This corresponds to the requirements

```
Coefficients

Term              Coef    SE Coef  T-Value  P-Value   VIF
Constant         12,79       1,56     8,21    0,000
Length (mm)   0,004185   0,000271    15,42    0,000  1,00


Regression Equation

Average = 12,79 + 0,004185 Length (mm)
```

Figure F.2: **Result of Minitab's Fit Regression Model for "4.8 Roll stack away" with only the variables that have a p-value of 0.050 or lower.**

for a regression model, according to Brook [2014].

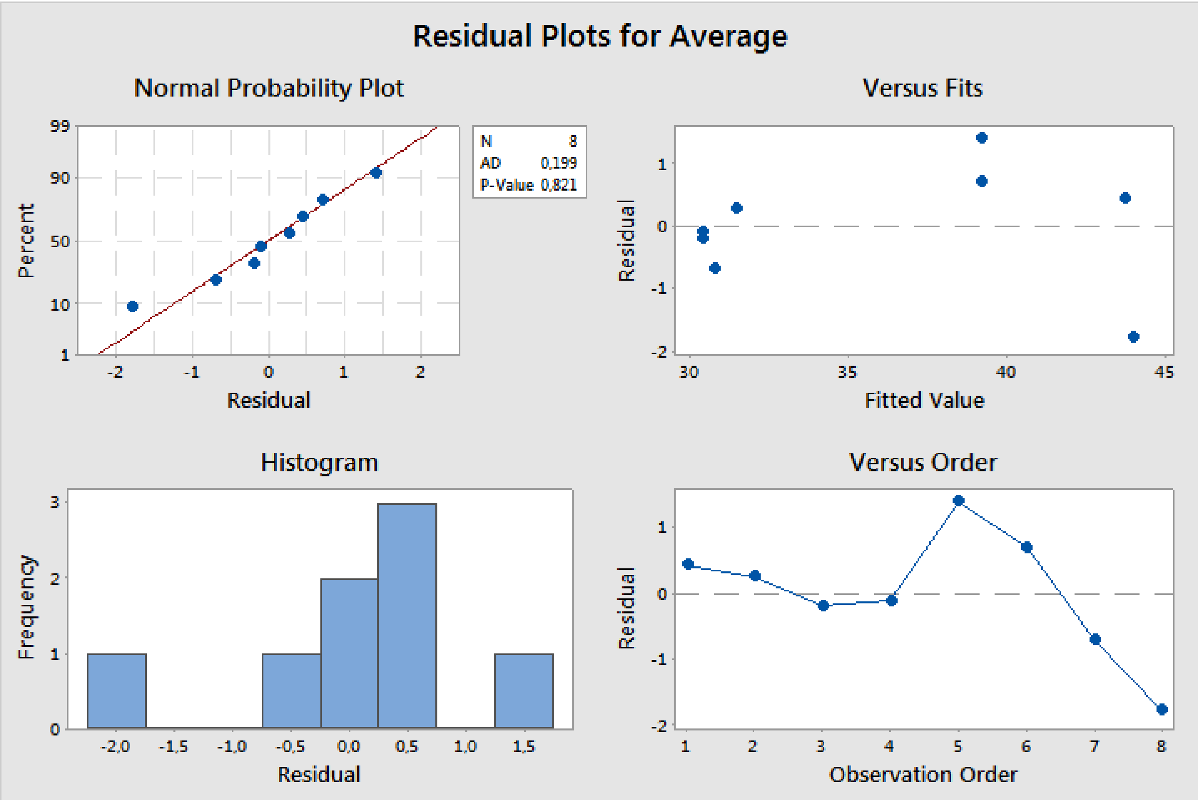


Figure F.3: **Residual plots for the regression model of "4.8 Roll away stack". The residuals seem normally distributed and random over the fitted values and observations, which satisfy the requirements.**

This method is done for all processes which are dependent on the input and for which it was decided to research further what the dependency on the input is. The results are given in *Table F.3*.

Processes	Constant (s)	Sheet thickness (mm)	Rip cuts	Cross cuts	Stack length (mm)	Stack width (mm)	Stack height (mm)	Sheets/parcel
1.11 Infeed scissor table (full) moves up	35.70						0.02	
2.2 Rip cut saw front cut	203.00	-0.20			0.00	-0.07		
2.3 Rip cut saw extra cut	151.40				0.00	-0.05		0.07
2.4 Rip cut saw back cut	185.50	-0.18	-2.36		0.00	-0.06		
2.5 Rip cut outfeed white belts moves parcel to cross cut	11.64							
3.1 Cross cut saw front cut	229.20	-0.51			0.00	-0.08		
3.2 Cross cut saw extra cut	16.06			-0.38	0.00			
3.3 Cross cut saw back cut	38.92			-0.75				
3.5 Cross cut outfeed rollers move parcel to stacking	27.32				0.00			
3.6 Cross cut pusher retreats	4.47				0.00			
4.1 Stacking parcel pusher pushes parcel on cookie tray	93.49	-0.06			0.00	-0.03		
4.3 Stacking cookietray (full) moves parcel on scissor table/stack	58.41	-0.03				-0.01		
4.6 Stacking scissor table (full) moves down	197.10					-0.06	-0.03	
4.8 Stacking outfeed rollers move stack to packing area	12.79				0.00			

Table F.3: **Process time dependency on input variables. When the process is not dependent on the input, it only has a constant, which is measured in seconds. When the process is dependent on the input, the factor that is in the table must be multiplied by the related property, on which the process time is dependent.**

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