BACHELOR THESIS

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Industrial Engineering and Management

"Continual and Continuous Improvement:

Combining the Theory Of Constraints and Lean Manufacturing"

Final Bachelor Thesis

Continual and Continuous Improvement:
Combining the Theory Of Constraints and Lean Manufacturing

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Preface

After a very interesting period packed with new experiences in South Africa, and a few weeks in the Netherlands, this report that lies before you is the final product. “Continual and Continuous Improvement: Combining the Theory of Constraints and Lean Manufacturing” contains a research in which we try to find suggestions to improve and optimize the performance of a production line at Aerosud in Pretoria. The research was carried out from October until December 2017.

I learned a lot during my research and for that I would like to thank some people in particular who supported me in my work during my period in South Africa. First of all, I would like to thank Eugene Nel. Eugene was my main mentor and supervisor during my stay at Aerosud and I had a lot of really good conversations and discussions with him which made the project significantly more interesting and the outcomes of the research better. Andre Tustin also helped me a lot, specifically with arranging this project for me, for which I’m also very thankful. Furthermore, I would also like to thank all my other colleagues at Aerosud and all the people I talked with for always willing and trying to help me.

During my research I have also been supervised on behalf of the University of Twente by Leo van der Wegen. With Leo’s help, I’ve learned a lot about documenting and motivating your work and about writing a scientifically well-structured report.

Furthermore, I also thank all the people that supported me in any other way during the past period.

I hope you enjoy reading this report.

Bas Hottenhuis

Management summary

Aerosud, a company located in Pretoria (South Africa), is an established leader in the aviation industry supplying integrated manufacturing solutions to big customers like Boeing and Airbus. Approximately 800 people work at Aerosud. Aerosud is a smart supplier, with capabilities ranging from programme management to design, development and production processes. Aerosud has great capabilities, ranging from design & development, metallic/composite/thermoplastic part production to assembly.

One of Aerosud's production line, the Vac-Form production line, should be optimized using the Theory Of Constraints and Lean Manufacturing principles. The specific problem that was given for this research is "Aerosud's Vac-Form production line *On Time Delivery* & *Quality* need to be 99%. Currently the line struggles to achieve the delivery performance while future increase in demands are immanent." In practice, Aerosud does perform good enough on the Quality KPI. So the goal of this research is to improve the On Time Delivery while not having to hand in on Quality.

The approach/structure within this research is based on the steps of the Theory of Constraints (TOC), a conceptual model that was made by H.W. Dettmer, and a literature research on lean tools and methods that can be used in combination with the TOC steps. We first describe the production line that we look at in this research. After that, the main structure of the chapters is 1) identifying the constraint, 2) Exploiting the constraint, 3) Subordinating, and eventually drawing a conclusion with some suggestions.

Identification of the process

We look at one specific production line, on which 287 different products can be made. The products are made in batches of approximately 10 products per batch. Products can go through the different production steps in several different sequences, but in this project we mainly focus on the main process flow which most of the products go through. For the identification of the production process, we made a production flow diagram and a value stream.

Identification of the Capacity Constrained Resource (CCR)

By using a Value stream Analysis and 4 other constraint identification methods, we found several potential CCRs. After analysing the potential constraints based on their expected impact on the system and the reliability of the data that is used for every method, we determined the Assembly cell to be the CCR in the system.

Exploiting the CCR: Exploiting the Assembly work cell

In this first step of TOC, we find improvement possibilities for the CCR. To find improvement possibilities, we make a simplified Current Reality Tree, we do some time and motion studies, and we use the lean tools that were identified from the literature. The improvement suggestions that result from these things are in short:

- The batches in the Assembly cell should be prepared, so the changeover time between batches

can be shortened.
- The batches that should be produced next or the finished goods shouldn't be handled by the artisans, so that they can keep working on assembling parts.
- Extra accessory should be bought so no time is wasted on searching for tools/jigs/etc.
- Production times per product should be determined. In that way, it is more clear for everyone how the cell is performing. In the current situation, artisans can spend a lot of time on simple jobs without anyone noticing it.
- The sequence in which the different batches are produced should be determined by the cell leader. For this to be successful, there has to be a clear priority system that is interpreted in the same way by everyone.
- Clear indications on the cell's current performance should be visible on the workshop floor. For this to be successful, the KPIs should be re-evaluated and directly linked to the company's KPIs.

All the suggestion mentioned above will increase throughput, or at least the throughput of the high priority parts. The total time that can be saved can be more than 10% with these improvements. This in combination with the fact that there will be more focus on the production of high priority parts will improve the On Time Delivery.

Subordinate
Here we focus on how we should change things in the rest of the production chain to help the Assembly cell produce even better/more. The suggestions that we come up with are:
- Pre-kitting the complete batches at the stores (work preparation cell)
- Setting a clear priority system throughout the whole chain
- Stopping with upstream batching, or at least only batch according to certain batching policies.
- Investigating the cause of all the Job Stoppers to prevent them from happening again
- Releasing the same amount of products every day to create flow in the system
- Visualizing the performance of all the cells throughout the whole chain.

Since these solutions are all a result of things that we've found in the previous TOC steps, most of them focus on helping the Assembly cell to perform better. The maximum impact of these improvements will for that reason also be more or less the same as the potential impact on the system that can be achieved with the improvements from the exploitation phase. This means that with a full implementation of the above mentioned suggestions can save 10% of the time and in that way increase the throughput significantly.

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Terms and definitions

TOC: the Theory of Constraints. The first main philosophy/theory on which is focussed in this thesis.

Lean (Manufacturing): philosophy for continuous improvement. The second main subject on which is focused on in this thesis.

WIP: Work in progress. The amount of products that have started the production process, but have not yet finished it. You can speak about WIP in a work cell (than it's ready to be processed by that work cell, but hasn't been finished yet) or about WIP in a whole line (obviously all the WIP added together).

Workshop: A production facility within Aerosud. The different buildings have been given numbers (e.g. the Vac-Form production line is in workshop 1)

PPS: Process Planning Sheet. Paper sheets bundled together. PPS's are used throughout the whole production process. Every batch has his own PPS that stays with the product from raw material until finished product, and depicts all the steps the product has to go through in the right sequence. If a product has been completed at a work cell, than that will be made visible at the PPS.

VSM: Value Stream Mapping. A lean tool with as end product a value stream. Used to get an overview of the whole (production) process.

DBR: Drum, Buffer, Rope. One of the main TOC principles

CCR: Capacity Constraint Resource. The constraint in the system based on the capacities of the different machines/work cells. Also known as the bottleneck. Most of the time, the constraint is a specific machine or work cell.

SMED: Single-Minute Exchange of Die. Reducing the changeover time by providing an efficient way of preparing the process for the next (different) batch of products.

SFDC: Shop Floor Data Collection. A software program to visualize all the data from the ERP-system. Also used in the workshop to scan a PPS to work on a product or to scan a PPS to finish the process. By scanning the current step from the PPS into SFDC, it is possible to see where every product is and which priority it has.

CT: Cycle Time. The time that is needed to produce one batch of products

CTPP: Cycle Time per product. The time that is needed to produce one single product

CO: Changeover time. The time that is needed to change the process for the next (different) batch of products.

COPP: Changeover per product. The time that is needed to change the process for the next product within the same batch.

KPI: Key performance indicator

AGS: Aircraft General Spare

Introduction

Research motivation

After organizing and being part of a study tour to South Africa, with as main subject being lean, I was really triggered to develop my knowledge and skills in this area even further. After returning I started searching for a suitable company and eventually found Aerosud Aviation. Aerosud was positive to take on this challenge together with me and invited me for an internship in their production facility in Centurion, Pretoria, South Africa.

Introduction of the company

Aerosud, a company located in Pretoria (South Africa), is an established leader in the aviation industry supplying integrated manufacturing solutions. Aerosud is a smart supplier, capable of adding value to partnerships involving programme management, design, development and production processes. Aerosud has great capabilities, ranging from design & development, metallic/composite/thermoplastic part production to assembly. The biggest customers of Aerosud include Boeing and Airbus for which they make a large number of parts.

My place within Aerosud is as an intern within the Continuous Improvement Team where I am going to look at the production department where products are made for airplanes. I am working at Aerosud during an 11-week period, from Monday October 2nd until Friday December 15th. My main mentor during this period is Mr. Eugene Nel. He is an Industrial Engineer at Aerosud and has worked here for more than 3 years now.

1. The problem identification

1.1 Problem as provided by Aerosud

The initial assignment, as given by Aerosud, is that we have to take a look at Aerosud's Vac-Form production line and try to optimize it using the Theory Of Constraints and Lean Manufacturing principles. The specific problem that was given to me regarding my assignment is "Aerosud's Vac-Form production line *On Time Delivery* & *Quality* need to be 99%. Currently the line struggles to achieve the delivery performance while future increase in demands are immanent." In terms of different types of problems, this practical problem could be considered as the action problem. Because the problem is already very clearly described, there is no need to make a further problem identification by means of for example a problem cluster.

1.2 Problem quantification: norm and reality

To be able to eventually say if the final solution is useful, it is of great importance to look at the problem and determine a norm on how the company aims to perform, and see how that holds in comparison to reality. Like mentioned in Section 1.1, the norm is to perform 99% on two KPIs: the *On Time Delivery* and the *Quality* of the Vac-Form production line. Both of the KPI's can be calculated very easily:

$$On\ Time\ Delivery = \frac{\#On\ Time}{\#Scheduled} * 100\%$$

$$Quality = \frac{\#Accepted}{\#Received} * 100\%$$

Both of the KPI's that Aerosud uses to determine how well they're performing, are KPI's from the customer. The values that are used to calculate the KPI's are also values that are determined by the customer. This means that the On Time Delivery mentioned above is the On Time Delivery at the customer. The number of products On Time, from the formula above, is the number of products that is delivered within the delivery window that's determined by the customer at the moment of ordering the products. Quality is also the quality in the opinion of the customer. All the products that are delivered at the customer will be checked by them and are either accepted or rejected. The value for the Quality KPI is a result from the values for accepted and rejected final products at the customer. That's how the values are calculated in theory.

The norm is to get a 99% performance on both of the KPI's. In reality, unfortunately, the performance isn't 99% for both of the KPI's. In Table 1 and 2, you can see the actual performance from the months August 2016 until August 2017. Table 1 shows the performance of Aerosud's Vac-Form production line for every month for the last year. Table 2 also shows the performance for every month, but the values for every month mentioned here are the average performances over the previous year. This means, for example, that the values in table two about the performance in the month August 2017 are the average values over the months September 2016 until August 2017.

As you can see in the tables, the values of the KPIs are pretty constant. For the last year, the Quality has always been above 99,9% (except for March when it was 99,69%). This means that Aerosud is performing really good at delivering Quality products, and they meet their goals. However, if we look at the On Time Delivery from August 2016 until May 2017, we see that the performance on the On Time Delivery has been around 97% or 98%, which means that Aerosud is performing below the norm. If we look at the last three months (June, July and August), we see a huge drop in the percentage On Time Delivery. This is due to a change at the customer shortening the delivery window from 10 to 5 days. For that reason, a lot of products were delivered a few days too late, causing a huge drop in the values. The effect of this can also be seen in Table 2.

BEST Code	Supplier Name & Address	SST-PST	Overall Supplier Performance Rating	Quality: Traditional Quality (% Accepted)	Quality: Alternate Quality	Delivery (% on time)	GPA	PFS
BE10002495	AEROSUD AVIATION PTY LTD VAN RYNEVELD & VAN DER SPUY ST SOUTH AFRICA		YELLOW	99.94%	~	82.55%	0	3.00

	August 2016	September 2016	October 2016	November 2016	December 2016	January 2017	February 2017	March 2017	April 2017	May 2017	June 2017	July 2017	August 2017
Traditional Quality	100.00%	100.00%	99.97%	99.97%	99.96%	99.97%	99.96%	99.69%	99.81%	99.97%	99.96%	99.95%	100.00%
•Received	5711.00	4754.00	4672.00	4774.00	2503.00	4577.00	5912.00	4860.00	4429.00	4509.00	5771.00	4852.00	6128.00
•Accepted	5711.00	4754.00	4671.00	4773.00	2502.00	4576.00	5910.00	4845.00	4421.00	4508.00	5769.00	4850.00	6128.00
Alternate Quality	~	~	~	~	~	~	~	~	~	~	~	~	~
Delivery	97.19%	96.84%	98.60%	98.90%	98.57%	96.51%	98.03%	98.28%	99.41%	96.84%	61.44%	54.83%	40.48%
•Scheduled	3634.00	3046.00	3217.00	3281.00	2519.00	3440.00	3824.00	3786.00	3082.00	3614.00	4158.00	4315.00	5988.00
•On-Time	3532.00	2950.00	3172.00	3245.00	2483.00	3320.00	3749.00	3721.00	3064.00	3500.00	2555.00	2366.00	2424.00
GPA	0	0	0	0	0	0	0	0	0	0	0	0	0
PFS	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Composite	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	YELLOW	YELLOW	YELLOW

Table 1 The customer's report Aerosud's performance (per month)

BEST Code	Supplier Name & Address	SST-PST	Overall Supplier Performance Rating	Quality: Traditional Quality (% Accepted)	Quality: Alternate Quality	Delivery (% on time)	GPA	PFS
BE10002495	AEROSUD AVIATION PTY LTD VAN RYNEVELD & VAN DER SPUY ST SOUTH AFRICA		YELLOW	99.94%	~	82.55%	0	3.00

	August 2016	September 2016	October 2016	November 2016	December 2016	January 2017	February 2017	March 2017	April 2017	May 2017	June 2017	July 2017	August 2017
Traditional Quality	99.91%	99.91%	99.92%	99.92%	99.92%	99.93%	99.92%	99.90%	99.90%	99.92%	99.94%	99.94%	99.94%
•Received	64088.00	64050.00	62481.00	62666.00	60436.00	60899.00	61254.00	60977.00	58266.00	57968.00	58381.00	57324.00	57741.00
•Accepted	64034.00	63996.00	62435.00	62619.00	60389.00	60857.00	61211.00	60921.00	58211.00	57924.00	58347.00	57290.00	57707.00
Alternate Quality	~	~	~	~	~	~	~	~	~	~	~	~	~
Delivery	96.25%	96.32%	96.31%	96.40%	96.80%	97.07%	97.08%	97.14%	97.17%	97.20%	93.65%	89.83%	82.55%
•Scheduled	41550.00	40980.00	40602.00	40800.00	40032.00	40317.00	41120.00	41283.00	40102.00	40781.00	41099.00	41916.00	44270.00
•On-Time	39994.00	39473.00	39105.00	39334.00	38752.00	39137.00	39921.00	40103.00	38971.00	39643.00	38491.00	37657.00	36549.00
GPA	0	0	0	0	0	0	0	0	0	0	0	0	0
PFS	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Composite	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	BRONZE	YELLOW	YELLOW	YELLOW

Table 2 The customer's report Aerosud's performance (average over the "last" 12 months, per month)

Furthermore, we also see GPA and PFS values. At Aerosud, they don't know what these values mean exactly, and nobody uses them. The fact that they are not used at Aerosud to check their performance means that we won't have to consider them any further.

What is more interesting from Table 1 and 2, is the colour scores of the KPI's itself (and the overall score on the lowest row). In the tables we see different colours in certain cells: Red, Yellow, Bronze (Brown), Silver (Grey) and Gold (Orange). The customer scores its suppliers with a colour-code on their performance. The meaning of the different colours can be seen on the right. The current overall score is Yellow, which is not good. This is mainly the result from the bad performance in the last three months.

CATEGORY	ON TIME DELIVERY	QUALITY PERFORMANCE
Gold	100	100
Silver	98.00 – 99.99	99.8 – 99.9
Bronze	96.00 – 97.99	99.55 – 99.79
Yellow	90 – 95.99	98 – 99.54
Red	0 – 89.99	0 – 97.99

1.3 Conclusion on the problem

The problem provided by Aerosud in the beginning was already very clear: "Aerosud's Vac-Form production line *On Time Delivery* & *Quality* need to be 99%. Currently the line struggles to achieve the delivery performance while future increase in demands are immanent". After analysing the norm and reality we have extra information on which we can draw further conclusions. Quality has always been sufficient while On Time Delivery has not. So, the most important conclusion that we can draw from the performance tables and problem statement is that the main goal of this research is to improve On Time Delivery, without having to hand in on Quality.

2. Theoretical framework

A theoretical framework serves to provide a well-structured approach for solving a specific action problem. Before a situation can be solved or improved there has to be an approach for solving it. We are elaborating on the theoretical framework in the rest of this chapter. The scope and theoretical perspective is within the operations management field. Since my main point of view is from the lean-perspective and Aerosud mainly has a TOC-perspective, the combination of these two is also is the theoretical point of view for this research.

2.1 Design of the literature research

This chapter serves to help us with answering our knowledge problem ("kennisprobleem"). The knowledge problem of this research is that we want to know how we can successfully combine Lean and TOC towards continuous improvement.

To get an answer on our knowledge problem, we first provide an answer to the questions "What is Lean" (Section 2) and "What is TOC?" (Section 3). In these sections we only use some basic references to give a general idea about the techniques, tools and methods that are used for both. These sections mainly serve to write down what we already know about Lean and TOC, and what their general meanings are.

After that (in Section 4), we discuss a model that was made by H.W. Dettmer (2008) in which a conclusion is drawn on how to combine lean and TOC in a conceptual model. This model gives us the basics for combining lean and TOC. We analyse Dettmer's model with regards to this project to determine what is still missing in our opinion and what the main focus of our literature research has to be.

In Section 5, we do a systematic literature research to get to know the information that we still need to know. The literature question that is answered in this literature research is more narrow than the knowledge problem that we have, because it focusses on something specific that we still need to know.

Eventually, we combine our knowledge about lean and TOC with the conclusions on Dettmer's model and the outcome of our literature research to get to a conclusion that will determine the activities in the rest of this research.

2.2 What is lean?

2.2.1 Lean in general

Lean is a very broad concept that, according to many, has his origins in the car manufacturing facilities of Toyota in Japan. In general, one could say that lean is a philosophy focussing on cost-reduction while eliminating different types of waste and constantly improving and maximizing customer value and quality of the product (Bicheno & Holweg, 2008). The main goal of lean is to reduce the cost over the whole process with no buffers between work cells.

2.2.2 Basic principles, tools and techniques

There is a large number of reports on lean, its methods and tools, the use of lean in different companies, and differences between lean and other related philosophies. From the knowledge gained in the bachelor study in combination with some basic references, we made a selection of some important principles, tools and techniques within the lean philosophy. Of course, every piece of literature has a slightly different view on them, but in general they are all using about the same descriptions. We briefly discuss a few of them below, to make the comparison between the literature pieces in a concept matrix easier to understand. These principles and techniques are also used within the rest of the research.

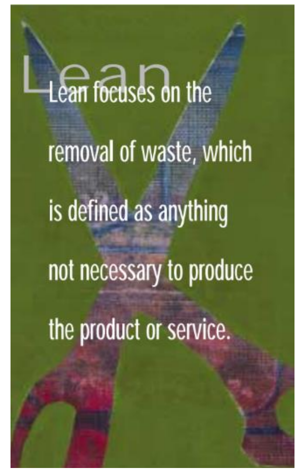

Figure 1, Nave, D. (2002)

Principle: Value, value stream, flow, pull, perfection

The main principles of lean and an important method to start implementing lean within a production environment are (Womack & Jones, 2003) :

- *Value*: What is the value of our product/what is important for the customer?
- *Value stream*: identify all the processes the product goes through to get an understanding of the value-adding steps.
- *Flow*: make sure all the processes happen in a smooth sequence while the product never stops in the process.
- *Pull*: work is only carried out when the result is required.
- *Perfection*: the constant strive of improving the process.

Principle: Muri, Muda, Mura

Japanese terms: Muri means a certain system overload, muda means waste and mura stands for variation/unevenness. The most important one of these terms is Muda (waste). Within lean manufacturing it is very important to eliminate all the things that don't add value to your end product. The different types of waste are often split up in: Transport, Inventory, Motion, Waiting, Overproduction, Over processing, Defects (TIMWOOD). Sometimes, an 8th waste is added: Talent.

Principle: Visual management

Visual management is about making processes clear and to be able to have a good overview of the situation. Visual management can be used in a lot of different ways and lean has several tools that can be used to implement visual management. By making processes visual, mistakes are easier to notice and problems can be solved more quickly. A well-known example of visual management is a two-bin system, or more general, Kanban.

Technique: 5S

5S is about simplifying your own work. This will eventually lead to making improvements. The 5S's stand for: sort, straighten, shine, standardise, sustain. The underlying goals are reducing waste and variation and improve productivity.

Technique: Value Stream Mapping

Value Stream Mapping (VSM) is a technique to get a clear overview of all the steps that are carried out throughout the whole process. A value stream can also show valuable information about a bottleneck in the system. A value stream describes all the steps: steps that are crucial, but also the unimportant steps. For all the steps, times are measured and noted (e.g. production time, set-up time or repair time). After completing this description, the importance of the different steps can for example be valued with colour codes. In this way you have a clear overview on which steps are crucial and which aren't. The steps that aren't necessary and also aren't value adding, should be eliminated. Furthermore, you also get a clear overview of what parts of the process take a lot of time, and where in the process large amount of work waits to be processed (WIP/inventory). The 2 major ways to identify a bottleneck from your value stream are by looking at steps in the process that are non-value adding and not necessary, or by looking at high numbers that stand out of non-value added time.

Technique: SMED

SMED is the abbreviation for Single-Minute Exchange of Die. The main goal of SMED is reducing waste. The manufacturing process should be shaped in such a way that the changeover times are minimized. A fast changeover between processes helps to create flow within a production line, which is one of the key concepts within lean manufacturing.

Technique: Poka-Yoke

Poka-Yoke is a Japanese term which comes down to making processes "fool-proof". It is a method that aims to shape a process in such a way that it is practically impossible to make a mistake. The process is shaped to force the different steps to be done in the correct way and in the right sequence. A good example of Poka-Yoke is the SIM card of a mobile phone that can only be inserted in one way.

2.3 What is TOC ?

2.3.1. TOC in general

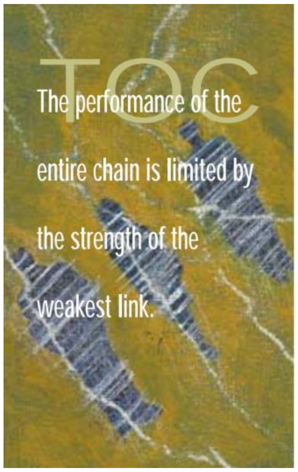

Figure 2, Dave, N. (2002)

The Theory of Constraints was originally introduced in 1984 by Eliyahu M. Goldratt, who is the author of the world famous book "The Goal", in which he first introduced the Theory Of Constraints in a novel. TOC can be used as a business management system that helps to continuously improve within an organization.

Generally speaking, the Theory Of Constraints says that the throughput rate of revenue generation is limited by at least one constraint/bottleneck. TOC also says that by improving the bottleneck, you will increase the overall throughput. In other words: The performance of a system at a given time is limited by only very few variables (maybe only even one!) (Goldratt & Cox, 2004). The main goal of TOC is to increase the throughput by concentrating on one work cell (the constraint) with only use of small buffers

2.3.2. Basic principles, tools and techniques of TOC

Just as with lean, there is a lot of literature that can be found about TOC. However, with TOC, there is not as much variation in tools and methods as there is with lean. As a result from that, it is easier to get hold of the different important aspects of TOC. Underneath we discuss a few important tools and techniques of TOC, based on some basic literature. These basics of TOC are also used for the final model that we use as a basis of this research.

Critical chain and the weakest link

The system is only as good as its weakest link.

Principle: TOC in five steps

There are 5 focusing steps within TOC. The steps are pretty straightforward to understand:

1) **Identify**:
   Identify the constraints in the system. In a system, there is always a weakest link. It is possible that the constraint is the market/demand. This is only the case if the production line can produce more than the demand. If this is not the case (like at Aerosud), then the system's constraint is a capacity constraint, also known as the Capacity Constraint Resource (CCR). The first step is only about analysing the process and choosing the system's constraint
2) **Exploit**:
   Decide what the desired situation is for the system's constraint and improve on the constraint. In this step a thorough investigation of the constraint is done searching for root causes and ways to solve it. The goal is to optimize the cell's output.

3) **Subordinate**: Make the decisions and changes needed as a result from the above decisions in the rest of the chain. The exploitation of the CCR can cause changes in the system. Therefore it is important to look at the whole chain and see if the exploitation has an impact on other cells.
4) **Elevate**: if the output isn't satisfactory yet, the system's constraint has to be improved further.
5) **Repeat**: When a constraint is fixed, go back to step one (watch out for inertia).

We can use these steps as a general outline for the research.

Principle: Drum, Buffer, Rope (DBR)

DBR is a very well-known concept of TOC. The principle of DBR is very similar to the principle of TOC in general: the output of the process is the same as the maximum capacity of the constraint in that process. The drum stands for the physical constraint (the CCR), which in most cases is a machine or work cell. The buffer, as the name already suggests, protects the drum for possible problems elsewhere in the system to keep the flow in the process. The buffer must make sure that the CCR can always keep producing. The rope is the mechanism that is used for releasing orders.

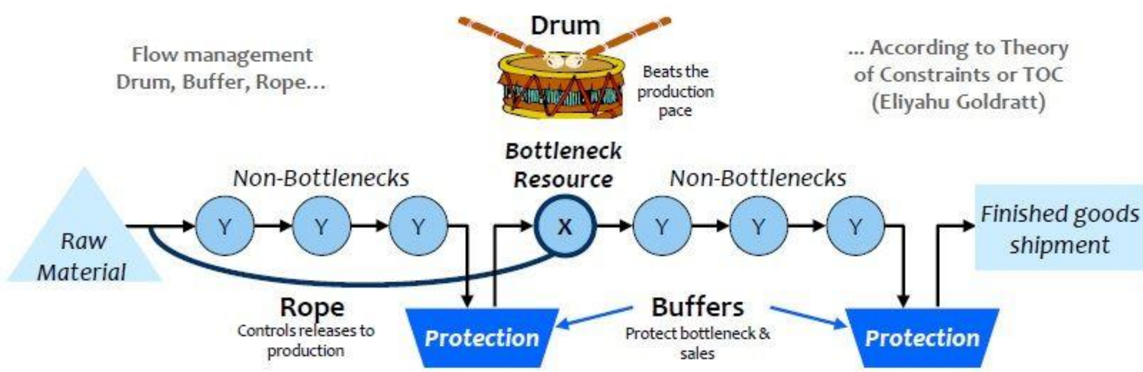

Figure 3: DBR visualization, from marris-consulting.com/en/training-news/training/training-theory-of-constraints on 18-9-2017

2.4 Dettmer's Model

A well-known academic writer about process optimization and especially about TOC is H.W. Dettmer. In one of his articles, "Beyond Lean manufacturing: Combining Lean and the Theory of Constraints for higher performance" (Dettmer, 2008), he compares lean and TOC. He finalizes with a conceptual model (Figure 4) which is based on the 5 steps of TOC. For every step, he mentions tools and methods of lean and TOC that can be used in that step. The model of Dettmer is a really good basis to determine what we want to do our literature research on. However, it is designed in a very general way, and therefore not applicable in every project. Therefore, we first analyse Dettmer's model to determine which parts of his model we want to include or exclude. Eventually, we use our conclusions on the included and excluded parts to determine what we need to know furthermore. The information that we still want to know determines what our literature question is.

1. IDENTIFY the system's constraint (TOC)
Identify the value stream (Lean)
Product/quantity assessment (Lean)
Process mapping (Lean)
Routing analysis (Lean)
Capacity determination (TOC)
Cell layout/design (Lean)
Standard work (Lean)
Roles and Responsibilities (Lean)

2. Decide how to EXPLOIT the system's constraint (TOC)
Kanban sizing (Lean)
  Transfer batch sizing (TOC)
One-Piece flow (Lean)
  Process batch sizing (TOC)
Backward plan (TOC)
"Drum" (TOC)
*SMED -CCR only (Lean)
*Poka-Yoke -CCR only (Lean)
*Kaizen -CCR only (Lean)
Graphical Work instructions (Lean)

3. SUBORDINATE everything else to the decision in Step 2 (TOC)
Kanban pull signal (Lean)
  "Rope" (TOC)
"Buffer" (TOC)
**5S housekeeping - Non-CCR (Lean)
**SMED - Non-CCR (Lean)
**Total Productive Maintenance - Non-CCR (Lean)
**Kaizen - Non-CCR (Lean)
**Training (Lean, TOC)

4. ELEVATE the system's constraint (TOC)

5. GO BACK to Step 1, but beware of inertia (TOC)

NOTE 1: *Activities indicated by a single star (*) are a combined engineering and system operator effort at the CCR. These activities are performed outside of normal production schedules (off-shifts, weekends, if possible) to minimize CCR downtime. These are HIGH PRIORITY efforts required to maximize available CCR capacity.*

NOTE 2: *Activities indicated by a double star (**) are largely system operator initiated and managed efforts at all non-CCRs (i.e., everywhere else except the CCR). These activities are performed during normal shifts, if possible, during idle time between production jobs. These are LOWER priority efforts, unless a non-CCR is in danger of becoming a CCR.*

Figure 4: integrating Lean Thinking and Theory of Constraints, Dettmer (2001)

Inclusion and exclusion of tools

Underneath we have made a selection about which tools to include or exclude. They have been split up in the TOC steps that Dettmer also uses in his model. For every step we give a short explanation about why we include or exclude that specific step. The including or excluding of tools or methods is based on the lean toolbox (Bicheno, J., & Holweg, M. , 2008) on the information that Dettmer gives in his article "Beyond Lean manufacturing: Combining Lean and the Theory of Constraints for higher performance" (2008) and on the book that Dettmer has also written: "Goldratt's Theory of Constraints: a systems approach to continuous improvement"(1997).

1. Tools to include:
   - Value stream mapping (VSM) is a very valuable method that is well known. The fact that it is used so much and its value has been proven several times is the reason that it will be one of the main techniques being used in the identification step. It is very helpful to get a clear overview of the processes, which is useful for identifying a constraint.
   - Process mapping and cell layout: useful for identification of the process. It's also a good way to get to know the process, which is specifically interesting in this case, because we don't know the process yet.
   - Routing analysis: part of VSM and Process mapping
   - Capacity determination: since increasing throughput is one of the main objectives of TOC, and the other tools in this step are in general lean tools, this is the most interesting thing of TOC that can be used as a tool for the constraint identification.

   Tools to exclude
   - Product assessment: There is only little information available about this. It isn't used that much. It also focuses on different product families, where we only want to look at the whole process in general. Therefore this tool is also less interesting to use in this project.
   - Standard work: Standardizing work is part of 5S, which is more interesting to use in the exploiting and subordination phase.
   - Roles and responsibilities: This is more the "soft" side of the improvement process and takes longer to implement in general. We have a technical point of view and not that much time available, so that's why we exclude this step.
2. Tools to include:
   - Kanban: part of visual management, which we already addressed before. Visual management can be easily be implemented with really good results, and therefore fits this project perfectly. We won't use whole Kanban because that's too broad. Instead, we focus mainly on two-bin Kanban systems.
   - "Drum": the drum from the whole drum-buffer-rope (DBR) idea as described before, during the exploitation, we only look at the CCR: capacity-constrained resource. In

other words, we have the focus on the Drum. This is not really a tool, but more an important principle that we have to take into account to realize that the CCR determines the production speed of the whole process.

- Poka-Yoke: focus on the CCR. Interesting because it reduces waste. Waste is often relatively easy to identify, which makes it interesting. This method also uses visual management, which is addressed before as really interesting for this project.
- Kaizen: A very broad term, basically meaning “good change”. A lean-principle that is good to use. However, the transfer batch sizing (TOC) that is considered as part of Kanban in Dettmer’s model is not as interesting, because there is not a lot information available about this.
- SMED: interesting because it reduces the time that is wasted. Since one of the main goals of this project is to improve on time delivery, this might be a really good lean tool to use.

Tools to exclude

- One piece flow: A really useful technique, but mainly interesting for continuous processes/the process industry, which isn’t the case in this factory (job shop environment).
- Backward plan: only little information available.
- Graphical work instructions: already implemented at Aerosud

3. Tools to include:
   - Kanban pull signal: a lean principle similar to the Rope of DBR in TOC. The goal is to keep the flow in the process. By using this Kanban/rope-principle, this is easier to realize. It applicable in a general way but you can also use it to go really deep. Because this project is only 10 weeks, it is interesting to look at this from a general point of view. We will combine the Buffer from DBR in this as well, because DBR is a well-known and proven to be useful principle.
   - SMED, Kaizen and 5S: same motivation as at the previous steps. However, in step 3 we have to focus on the non-CCR resources.

   Tools to exclude
   - Training and Total Productive Management: takes a lot of time and we do not have enough time available for that.
4. This step is focussing on elevating the system’s constraint. This is done after the constraint has been exploited, and also after the whole system has been subordinated. We will simply not have enough time to do this. That’s why we only focus on the first three steps of TOC.
5. See step 4: not enough time available

Conclusion on Dettmer's model

In this section, we looked at all the tools and methods that Dettmer uses in his model and identified which tools and methods we want to use in this specific project. If we look at all the inclusion decisions that were made, the following tools are left to be used:

1: identify	***2: exploit (CCR focus)***	***3: subordinate (Non-CCR focus)***
VSM	Kanban (visual management)	Kanban pull /"Rope" principle of DBR
Process mapping	"drum"-principle of DBR	"Buffer"-principle of DBR
Cell layout	Poka-Yoke	5S
Capacity determination	Kaizen	Kaizen (visual management)
	SMED	SMED

In the table above, we have capacity determination, DBR and the TOC-steps as the only TOC tools/methods/principles, from which the capacity determination is the only real tool that can be used. This is partly a result of the fact that Dettmer doesn't use a lot TOC tools in his model and also because we eliminated a few TOC aspects from Dettmer's model, because they can't be used in this situation (e.g. because they don't match with Aersoud's way of producing or because we don't have enough time for them). Since we don't know much about TOC yet, and because it's also not covered enough in the resulting tools and methods in the table above, we focus primarily on TOC in the literature research.

We think it's important to find more information about TOC tools and methods that can be used for the implementation of TOC. This can be combined with the conclusion on Dettmer's model to make a model that can be used in the rest of this project.

2.5 Systematic literature research

The main goal of the literature research is to help us to find an answer to our knowledge question: how to combine lean and TOC. We already know quite a lot about lean, and less about TOC. In the previous section, we also looked at Dettmer's model to determine about what we still want to know more. Dettmer's model is a good basis to answer our knowledge question, but after deciding on which tools and methods we want to include in this specific project, there were only a few TOC tools and methods left that we want to use. For that reason, we do a systematic literature research that's mainly focused on TOC. In this way, we can decide how we can involve TOC more in our final model. Since the main goal is still to combine the knowledge about TOC with lean, this will also be in the formulation of the literature question.

The literature question that we answer with this systematic literature research is:

"Which tools and methods are used for a successful TOC implementation and can be used to combine with Dettmer's model? "

To answer this question, we do research about tools and methods that can be used for TOC that we don't know about yet. Since we also want to focus on the *successful* implementation of it, we also look at success factors, barriers, obstacles and strength or weaknesses while implementing TOC. The literature research protocol can be found in Appendix A. As you can see, most of the terms focus on TOC, and only one on the combination of TOC and lean. That's because our main focus is on trying to find extra TOC information to add to our result from Dettmer's model. The research for tools and methods etc. will only be focused on the first three steps of TOC, since these are also the only steps that we are going to look at for this whole project.

In this chapter, we start with extra information about TOC: tools, methods, techniques and principles that we haven't covered yet (Section 2.5.1). This focuses only on TOC, because this is the focus of our literature question.

After that, we look at barriers, strengths and weaknesses and make a concept matrix (Section 2.5.2) containing the information from our literature research. This concept matrix shows information about both lean and TOC. We do this because we haven't covered any of the barriers, strengths or weaknesses of lean either. The concept matrix is made to give an overview on both lean and TOC.

Eventually we combine the conclusion on Dettmer's model with the extra information that we have found about TOC to make our own conceptual model. The information from the concept matrix about barriers/strengths/weaknesses of TOC and lean is analysed to see how we can use this our how we should take something into account at a certain step.

2.5.1 Which tools and methods are used for a successful TOC implementation?

To keep a clear overview, the lay-out of this part of the literature review is based on the first 3 TOC steps that we want to address. We first discuss specific tools/methods/principles that are important for every TOC step. After this, we will draw a conclusion on what can be used in this research.

The useful tools, methods and principles that we have found for every TOC step are:

Identify:

Methods: Four constraint identification methods

The bottleneck within a production system is also called the constraint of that system. In the literature there are a few major bottleneck/constraint identification methods (Bell, 2005) (White, Sengupta, & Vantil, 2012) (Sims & Wan, 2015). The main and most important ways that we have found to identify the system's constraint are:

1. The machine with the largest WIP

Look at the large accumulations of WIP (work-in-process) on a specific work cell on the plant floor. WIP is the amount of products that have started the production process, but haven't finished it. Inventory/WIP often accumulates before/at the bottleneck.

2. The machine with frequent expediting/firefighting

Look for areas where some sort of process expeditors are often used. This can be seen by looking at places were people often have to get extra material or quickly have to do things to speed the process up. This is often the case at the bottleneck to ensure that the critical orders are completed on time.

3. The machine with the largest percentage of fail state.

Look at the machine with the greatest percentage of fail state: the relative percentage of time in which the machine is broken and can't be used. A machine that is broken a lot can be the constraint of the system. The percentage of fail state is calculated by dividing the time in fail state by the total time (fail state + working state).

4. The machine with the highest utilization.

Look at the utilization of the machines or work cells in the production line. The machine with the highest relative utilization can be the system's constraint. The machine utilization is calculated by dividing the practical by the theoretical capacity of the machine. The practical capacity is the capacity that is needed to produce all the products that are demanded. The theoretical capacity is the capacity that is available to use on that that specific machine or work cell.

Other bottleneck/constraint identification methods that are mentioned in the literature are similar to one of the 4 above, or have the same basis as one of the 4 methods. That's why we choose to only use the methods mentioned above. The four methods can all be used to identify the bottleneck/constraint. After using all the methods and identifying the bottleneck from every method, it is possible that they will have different outcomes, resulting in different bottlenecks. The result of this is that we might have four different potential constraints. After using the methods and identifying the potential constraints, it's important to evaluate the potential constraints that have been found. We have to look if some of the potential constraints can be eliminated from being the actual constraint because the methods that are used are less reliable than others. For example if a certain method only captures a single state of the system then that data is less reliable, so the potential constraint that resulted from that method can be eliminated. When that has been done, the remaining methods can be analysed on reliability with regards to the data that is used for each method. The constraint that resulted from the method that is the most reliable is chosen as the system's constraint, which is the result from the first TOC step.

Method/tool: Throughput accounting

Througput accounting (TA) is considered as one of the main techniques that can be used in TOC. TA fits TOC really good since TOC focusses on improving the throughput of the system instead of decreasing the cost (Goldratt). Througput accounting is a technique that looks at the system as a whole and its capabilities. (E. Du Plooy, 2016).

The basis of throughput accounting says that you have to look at the time that is available in a year to produce products (for every work cell). This is 365 days a year, minus all the weekends, public holidays etc.. After this, you need to subtract other times in which is cell can't produce any products (maintenance, breakdown times, set ups, etc.). you're now left with what Du Plooy calls the Productive capacity. Du Plooy also states that you don't want your cells to run 100% of the time. In that case you will have a big problem when something goes wrong. Therefore we apply a "Protective Capacity" of for example 10%. This protective capacity protects the system against any problems as a result from variation. If you subtract the protective capacity from the productive capacity, you have the system's net (productive) capacity. There are several ways to continue after this step. You can choose to look at the system at the current day, including all the information about backorders, future demand, and finished goods. You can also look at it in a more general way, and only consider the information for a whole year. In this case, you determine the "net load" of every work cell per year (using product groups, demand per year and production time per product).

This general way is very interesting for this project for the constraint identification phase. Du Plooy says that a high capacity utilization is an indicator of a possible problem/bottleneck/constraint. This method has a lot of overlap with constraint identification Method 4 on the previous page. Therefore, it is interesting to use throughput accounting to determine machine utilization for constraint identification method 4. To get a better understanding of throughput accounting, we've made an easy example that can be found in appendix B.

Exploit:

Principle of exploiting

The main principle behind exploiting the constraint is not only improving it but more about getting the most out of the constraint without committing to potentially expensive changes or upgrades (Dettmer, 1998)

Method: Key measurements

The three main things to measure if you're improving your system are: Throughput, Inventory and Operating Expense (Goldratt,2004) (Dettmer, 1998)
Thoughput = the rate at which the entire system generates money through sales
Inventory = all the money the system invests in things it intends to sell
Operating Expenses = all the money the system spends turning inventory into throughput

So the goal of every action must be increasing Throughput or decreasing Inventory or Operating Expenses. So for every decision that is made to exploit the constraint, one must think if it does influence one of these three measurements.

Tool: Current reality tree

A current reality tree is part of TOC thinking process (Dettmer, 1997). The starting point of this thinking process is a Undesirable effect (UDE). From this UDE (for example: we don't produce quick enough) you should ask yourself what the reason is for that a few times. By doing this, it's often easy to find your root cause or improvement possibilities.

Subordinate

For the subordination phase, the literature doesn't really provide TOC tools or methods that can be used. Most of the time it also depends on the decision that's made and how/if that influences any other cells. It does however give some rough suggestions on what can be done to subordinate. Some of the suggestions that are interesting are:

- Detune certain cells or revving up others (Dettmer, 1998)
- creating flow by producing the same amount of products every day (Goldratt, 2004)
- Visualize how the constraint is performing for everybody (Dettmer, 1998)
- Let other resources help the constraint (Rahman, 1998)

Conclusion on TOC tools and methods

In this Section, we looked at tools and methods that can be used for a successful TOC implementation. Concluding from the different findings of this Section, we have different tools and methods to combine with Dettmer's model. In the table below, we have made an overview on the possible TOC aspects that we can combine with Dettmer's model.

1: identify	***2: exploit (CCR focus)***	***3: subordinate (Non-CCR focus)***
Constraint identification methods	Base choices on the key measures	Create flow
Throughput Accounting (for CCR identification)	Current reality tree	Visualize how the constraint is performing for everybody
		Let other resources help the constraint

2.5.2 Which barriers/strengths/weaknesses have to be taken into account when implementing lean/TOC and how do they compare to each other?

Furthermore, part of our literature research is also to look at the strengths and weaknesses. In this section we will look at barriers, strengths and weaknesses of both lean and TOC. Because we haven't discussed any of them before for lean or for TOC, we will now make a concept matrix giving us an overview for both of the philosophies to make the comparison easier. After the concept matrix is made, we draw a conclusion on how this can be used for our final model. The main goal of the concept matrix is to get an overview on possible extra additions to Dettmer's model. The matrix is a result from previous knowledge and from the literature research that we did. On the lean side, we mainly filled in information that we knew and which was reconfirmed by some of our literature. For the TOC part, we found all the information during our literature research.

This concept matrix answers different questions:

- What are the barriers when implementing lean or TOC?
- What are strenghts of lean or TOC?
- What are weaknesses of lean or TOC?

Behind every statement, you can find the number of the article in which it is mentioned (numbered literature is on the next page). Furthermore, characteristics of lean and TOC and the barriers that may occur while implementing them are also added to the concept matrix. The aspects mentioned in this concept matrix are the reason why some additions are made to Dettmer's model.

Table 3: the concept matrix

	Lean		**TOC**	
	Barriers with implementation			
General	It is difficult to get full dedication of all the employees (1, 4)		Can take a longer time before it is really successful in the whole chain because other constraints "pop up" after solving the chosen constraint (1, 3, 4, 6, 14)	
Start of the process	Misinterpretation on how to use lean because it can be used in a lot of different ways (5, 8, 9, 10, 12)		Identifying the bottleneck is hard because there are a lot of things that can influence the data. Seeing which influences exist is sometimes really hard (1, 2, 4, 11, 13, 14)	
Communication	Lack of communication leads to misunderstanding for the workers about what lean is (1, 3, 4, 6, 10)		If there's not enough communication with all the workers then it's hard to identify the right constraint (1, 3, 6, 10, 11)	
	Strength	***Weakness***	***Strength***	***Weakness***
Scope	Rapid succession through small improvements (4, 12)	Too broad/no focus and takes a lot of effort over a long period (1, 2, 3, 6, 9)	Strict focus on bottlenecks makes it easy to keep an overview (1,2,4, 14, 15, 16)	
Combination with other techniques	A lot of similar philosophies to combine with (5, 8, 9, 12)		Independent origin (2, 8, 16)	No usual combination with similar techniques (6, 9)
Peoples aspect	Respect for people is always considered (1, 2)	People involvement is essential, which is sometimes really hard to accomplish (1, 4)		Creates a gap between Management and workers (1, 2, 9)

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Conclusion on the matrix

We split up the conclusion of this matrix in two parts: the barriers and the strengths/weaknesses. In this conclusion, we determine which barriers/strengths/weaknesses have to be taken into account when implementing lean/TOC. In the matrix it can be seen how they compare to each other.

If we look at the barriers, we have three categories. The first category is general, and says that with lean it’s hard to get the full dedication of the employees, where at TOC the problem is that a new constraint can pop up after solving the chosen constraint. We will have to take into account that it’s hard to get full dedication of everybody and try to include them as much as possible to create more dedication. The fact that a new constraint appears after solving the current constraint is a barrier/problem when trying to solve a problem, but unfortunately, this can only be solved after a few TOC cycles, so this won’t be part of the scope of this project.

The second barrier category is about barriers at the start of the process. For lean, there are a lot of different ways to implement it, which can give unclearness and misinterpretation. For TOC it is mainly hard to find the right bottleneck. Regarding the lean barrier, we have to make sure that we communicate as good as possible (e.g. weekly update meeting) and discuss how everybody thinks things are going and how things should be done. For TOC, with identifying the bottleneck, it is important to not rush this stage. This stage needs a lot of attention with a good investigation of potential constraints.

The third category is communication. In lean terms, the actions on this barrier are about the same as with the second category. However, in this case, we also need to focus on good communication with all the employees in the workshop for example by telling them what we are doing and what we are going to do every time we speak to somebody new. This way of working also helps to solve problems with the TOC barrier, that's also mainly about communication with the workers on the workshop floor.

If we look at the strength and weaknesses, we also have three categories: the scope, combination with other techniques and the peoples aspect.

From the scope category, we can use the strength of lean (rapid succession through small improvements) at the exploitation phase. The fact that lean is sometimes too broad without enough focus is already solved because the use of the TOC steps, which focusses on one specific constraint before looking at the bigger picture.

The last category is the people aspect. The good thing about lean is that respect for the people is always considered. On the other hand, the involvement is also essential for a successful implementation. We don't want to experience this gap, so we have to involve the people on the workshop floor as much as possible. By doing this, we will also solve the problem that occurs at TOC that is the creation of a gap between management and work floor. This has to be taken into consideration at every step.

Concluding from this concept matrix, the most important points are discussed above and shown below. We chose to show them in an overview based on the TOC steps, so it's easier to combine with Dettmer's model.

1: identify	***2: exploit (CCR focus)***	***3: subordinate (Non-CCR focus)***
Including workers to create more dedication	Lean tools achieve rapid successes through small improvement	Lean tools achieve rapid successes through small improvement
Keeping stakeholders up to date (workers + mentor + management)	Involve all the different kinds of stakeholders (from workshop workers to management)	Involve all the different kinds of stakeholders (from workshop workers to management)
Use constraint identification methods		

2.6 Final conclusion

The conclusions about our literature question is based on Section 2.5.1 and 2.5.2 and the knowledge that we already had. In this Section, we describe the result of the previous paragraphs to give an answer to our literature question:

“Which tools and methods are used for a successful TOC implementation and can be used to combine with Dettmer’s model? ”

This literature question (which is also our first research question), is answered by making an own model that is going to be used in the rest of this research. Like addressed before, our model is essentially based on Dettmer’s model. In Section 2.4, we described the useful and the less useful tools and techniques from Dettmer’s model. In addition to this, in Section 2.5.1, we found some useful TOC tools that can be added to Dettmer’s model. Eventually, in Section 2.5.2, we looked at barriers/strengths/weaknesses of both TOC and Lean, which we should pay attention to during every step. In all the sections we drew a conclusion that matches the first three TOC steps. Underneath, we repeat those conclusions. After that, we combine them to come to our final model.

Tools that were interesting from Dettmer’s model are:

1: identify	***2: exploit (CCR focus)***	***3: subordinate (Non-CCR focus)***
VSM	Kanban (visual management)	Kanban pull /”Rope” principle of DBR
Process mapping	“drum”-principle of DBR	“Buffer”-principle of DBR
Cell layout	Poka-Yoke	5S
Capacity determination	Kaizen	Kaizen (visual management)
	SMED	SMED

Tools that were interesting from the TOC literature are:

1: identify	***2: exploit (CCR focus)***	***3: subordinate (Non-CCR focus)***
Constraint identification methods	Base choices on the key measures	Create flow
Throughput Accounting (for CCR identification)	Current reality tree	Visualize how the constraint is performing for everybody
		Let other resources help the constraint

Things to pay attention to, to prevent us from falling for common barriers and to maximize the results of the good aspects of both of the philosophies are:

1: identify	*2: exploit (CCR focus)*	*3: subordinate (Non-CCR focus)*
Including workers to create more dedication	Lean tools achieve rapid successes through small improvement	Lean tools achieve rapid successes through small improvement
Keeping stakeholders up to date (workers + mentor + management)	Involve all the different kind of stakeholders (from workshop workers to management)	Involve all the different kind of stakeholders (from workshop workers to management)
Use constraint identification methods		

For the identification phase, we can use VSM, Process mapping and Cell layout and capacity determination from Dettmer's model. In addition to this, we found the constraint identification methods that can be used in the first TOC step and Throughput Accounting. Throughput accounting has a lot of overlap with capacity determination (but is a bit broader), so these will be taken together and replace the fourth constraint identification method that focusses on machine utilization.

Things to pay extra attention to are: including the workers to keep them dedicated and keep all the other stakeholders up to date all the time.

For the exploitation phase, we can use Kanban (visual management), the Drum-principle, Poka-Yoke, Kaizen and SMED. In addition to this we found the three main measures to check your improvements on: increasing throughput, decreasing inventory or decreasing operational expenses. In this step it is also very useful to use current reality tree analysis to find root causes and solutions for the constraint.

Things we pay extra attention to are the use of lean tools that were mentioned earlier to achieve rapid successes through small improvements. This is also why we will focus on the quick, easy, and small improvements in this step. In this step we also have to involve all the different kinds of stakeholders.

For the subordination phase, we can use Kanban-pull/the rope-principle, the buffer-principle, 5S, Kaizen and SMED. We didn't find really new tools or methods in our literature research, but possibilities are to use visual management or to let other non-constraint resources help the constraint resource.

Things we pay extra attention to are the same as with the second TOC step: use of lean tools that were mentioned earlier to achieve rapid succession through small improvements involving all the different kind of stakeholders.

We take all this information together and finalize this chapter by making our own final conceptual model. The conceptual model (Figure 5) is a result form things that we knew and from literature research and tries to give an answer to our knowledge question on how to combine lean and TOC. This model is used as an outline for the rest of this project.

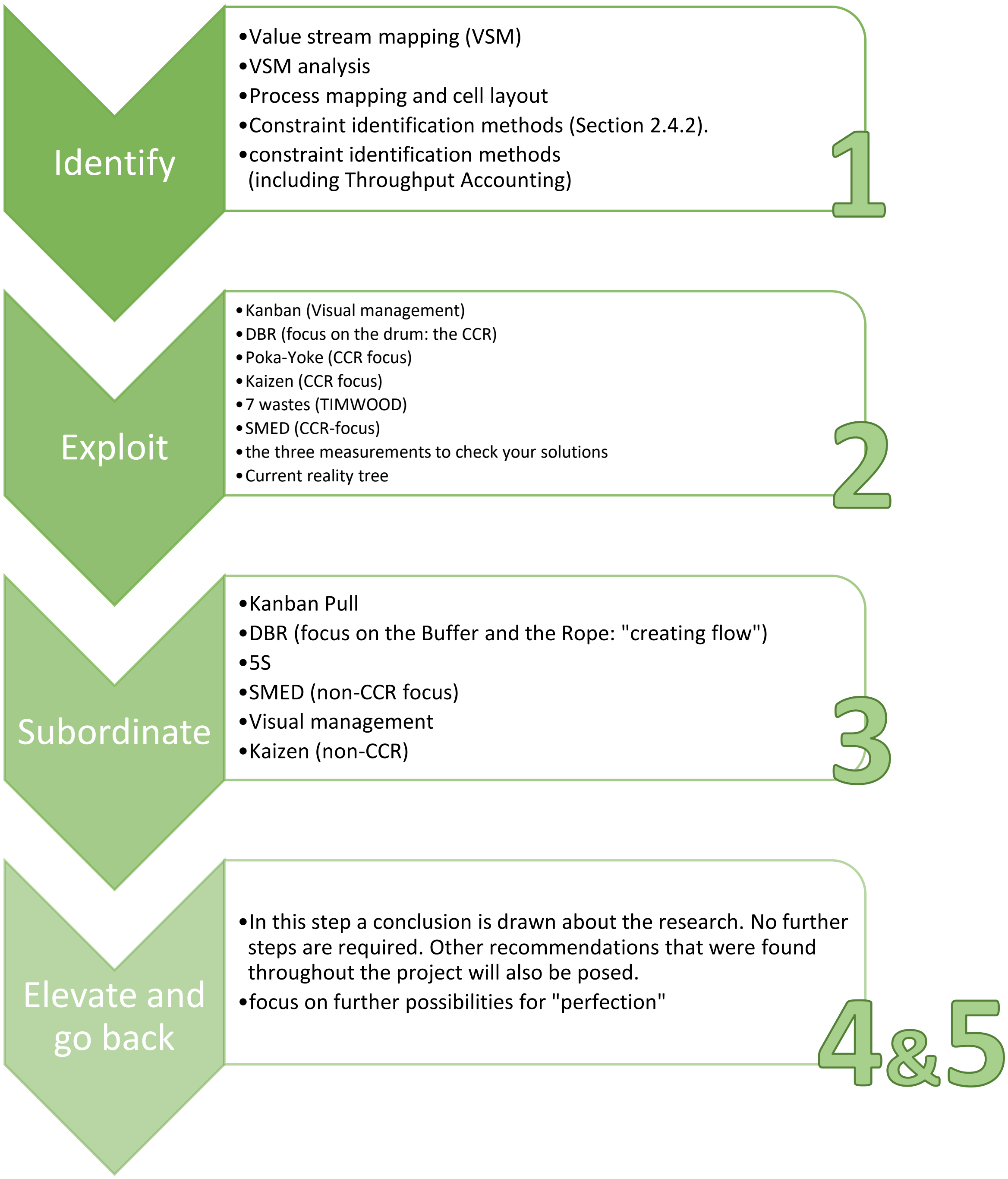


Figure 5 Model for successfully implementing TOC in combination with lean

3. Research approach

3.1 Research goal

The goal of this research is to find out what causes the problem provided, analyse it using Lean and TOC, and eventually draw conclusions on how the current situation can be improved. When the time allows us, we also try to give a proposal on what should be improved and what the implementation process should look like.

3.2 Research approach

The research approach used is important because it is a procedure that is used for all the research activities within this research. The type of research used in this report is exploratory research: a form of research that aims to provide insights into, and deeper understanding of a problem that is in this case provided by Aerosud. Apart from that, it is also desirable to find possible solutions/improvements for a current situation. This will be done on basis of the research questions stated in Section 3.3.

3.3 Research questions

It is useful to work with main research questions. Throughout this report, all the research and analysis will be done with as final goal to answer the research questions. The research questions are based on the initial problem that was provided by Aerosud in combination with our conceptual model. The initial problem is: "Aerosud's Vac-Form production line *On Time Delivery* & *Quality* need to be 99%. Currently the line struggles to achieve the delivery performance while future increase in demands are immanent." And the conceptual model can be found in Chapter 2 (Figure 5).

The research question are as follows (including a short explanation on what every question means):

1) **Which tools and methods are used for a successful TOC implementation and can be used to combine with Dettmer's model?** (literature question which was covered in Chapter 2)
2) **How exactly does the production line work?**
   In this research question, we identify all the different steps within the process. We make a process flow diagram and a good value stream with all the needed explanations to try to get an understanding of the process as good as possible.
3) **Step 1 of TOC, Identify: How does the system currently perform and what is the system's constraint?**
   1. **What is the current performance?**
      We give an overview on the performance of the different work cells, from which a conclusion can be drawn on what the constraint is. Data has to be gathered to show what the current performance is. The main activity for this sub-question is

doing a value stream analysis and working out the 4 constraint identification methods.

2. **What is the system's constraint?**
Choosing the actual constraint and giving an explanation on the choice that is made. Mainly based on the VSM-analysis and constraint identification methods outcomes and an short analyses on how reliable the data is that was used to determine the constraints.

4) **Step 2 of TOC, Exploit: How do we want the system to perform and how can we improve the constraint? (focus on CCR)**
In this chapter, we determine how the constraint in the system should perform and how we can change it. This is about the performance of the specific constraint, and not the whole system. Therefore, we need to analyse the data that's available about the chosen constraint, to determine what should change. In this step we thoroughly investigate the CCR, the critical points at the CCR and possibilities for improvement. The final goal of this step is to have several small improvements that can be implemented quickly without costing a lot of money.

5) **Step 3 of TOC, Subordinate: What changes can/must be made in the rest of the system to improve the productivity of the CCR if we look at the whole system? (focus on non-CCR cells)**

   First, we have to make an overview on the outcomes of the different solutions in Step 2. Then we have to look how this could influence other cells. If the decisions could influence other cells, then we have to focus on changes in these cells first. If the decisions in Step 2 don't directly influence other cells in the system, then we can look at general improvement possibilities for the whole system.

After consultation with the stakeholders and our own idea about the best improvement, we make a solution matrix to choose one solution. If the time allows us to, we also try to make a short implementation plan (CCR and non-CCR)

The structure of the research questions is a result from the 5 TOC steps. These questions are also the general framework for this research. Every research question has his own chapter. The main goal of every chapter is answering the research question.

3.4 Delimitations and barriers

3.4.1 Delimitations

To keep the research specific enough, some delimitation have to be set. This means that the scope of this research will be only within the Vac-Form production line. When a specific constraint is identified, the scope of the project will be even more narrow by only focussing on that constraint.

3.4.2 Barriers

The barriers that are present during the research are the same barriers that occur within lean implementation or TOC implementation. In the concept matrix, we already discussed how we are going to make sure these barriers won't have too much influence on the process (Section 2.6), so we won't be elaborating any further on this here. On top of those barriers mentioned, there is also a big time constraint. Because there's only a short period of time available, the assignment can't be too broad. It should be possible to investigate the process, answer all the research questions, and write the bachelor thesis within 10 weeks.

Furthermore, it is also likely that there are cultural barriers. The culture in South Africa is much different from that in the Netherlands. This has to be realized to make sure that this doesn't cause any problems. There are a lot of different ways in which cultural barriers could occur. They are the easiest to consider using the cultural dimensions (Hofstede, 1984). The cultural dimensions from Hofstede can be found in Figures 6 and 7. An explanation of the different dimensions can be found in appendix C. What stands out in Figure 6 is the difference between South Africa and the Netherlands when it comes to masculinity (focus on achievements and success) and long or short term orientation. This might be important to realize during the rest of this project. How we can use this in this project is for example by telling people they did something good or that they have good ideas that we can use (some sort of an achievement).

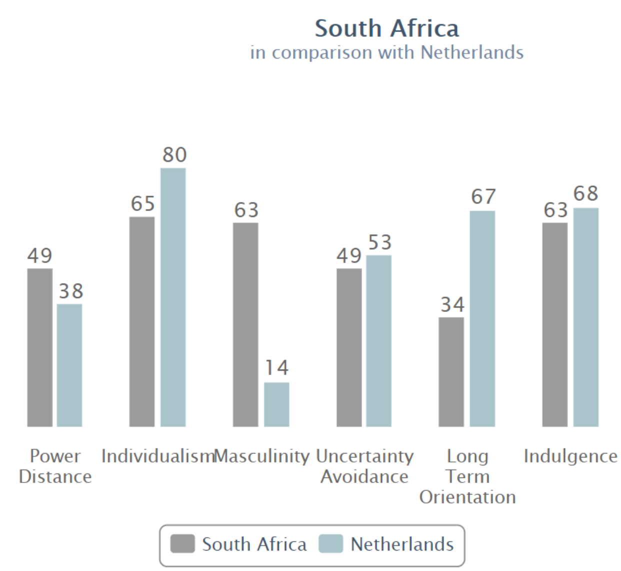


Figure 6: South African compared to Dutch culture

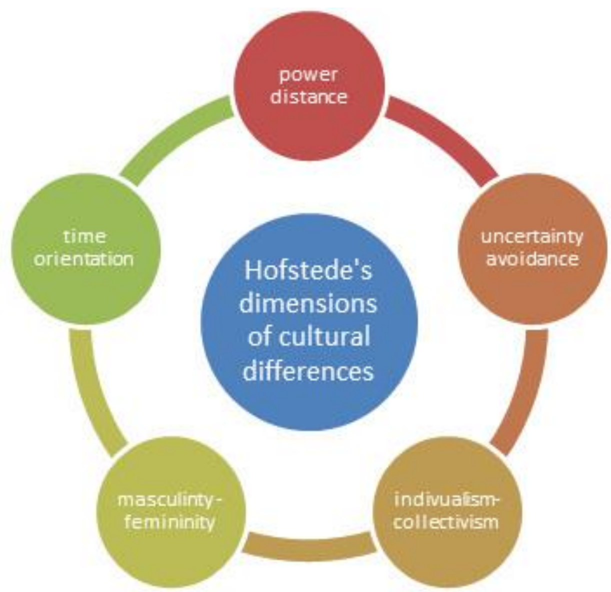


Figure 7: Hofstede's cultural dimensions (1984)

3.5 Data validity and reliability

Most of the data that we are going to use will be subtracted from the ERP-system (mainly the software system that uses the ERP as an information source) or will be a result from conversations/interviews with employees at Aerosud.

Reliability

When we subtract information from the ERP system, we should never trust the data immediately. If products are registered in the system several times in different ways for example, then that can give a skewed image of reality. For that reason we should always look at which data is used to calculate the data that we want to use. When we gain information from conversations/interviews with employees at Aerosud, it is important to not immediately believe everything they say. This is not because the employees are lying, but because people can have different perspectives on certain issues. Therefore, we should always verify all the information by asking the same questions to different people. In this way our view on reality will be most reliable.

Furthermore, Cooper and Schindler (2014) also mention three things which make reliable data practical for use. Those are: economy, convenience, and interpretability. Economy is not really relevant because there are no costs attached to this research. Convenience will probably also not be a problem, because we simply don't have the time to make the research really complex. The Interpretability issue is mainly important to keep in mind for the report, so that everyone that reads the report can get a good understanding of what is said. So all in all, we have to try to get data as reliable as possible which is easy to interpret for the readers of the report.

Validity

If we look at the validity of data in the context of this research, we can look at it using some different forms of validity. Those forms are (D.R. Cooper & P.S. Schindler, 2014):

- **Content validity** exists to the degree that a measure provides an adequate reflection of the topic that's under study. The determination of this measure is mostly intuitive. This form of validity is therefore relevant to keep in mind when analysing interviews/conversations, because a lot of this analysis often depends on intuition.
- **Criterion related validity** relates to our ability to predict some outcome or to estimate the existence of some current condition. This form of validity is mostly interesting for us to keep in mind during the process identification, because we won't have enough time to do thorough time studies of everything, which is also the reason that we will maybe have to predict some outcomes.
- **Construct validity** is quite complex and abstract. A measure has construct validity to the degree that it conforms to predicted correlations or theoretical propositions. Since we don't really use any correlation predictions and also don't compare any outcomes to theoretical propositions, this is a form of validity that we won't really have to keep in mind.

4. Description of the production line

In this chapter we answer the second research question, which is mainly a preparation for the third research question that covers the first TOC step. The research question that is answered in this chapter is:

How exactly does the production line work?

To answer this question, we do different things. In Section 4.1, we identify the complete factory layout. After that, in Section 4.2, we zoom in on the production line on which we are focussing during this project. In this section, we also identify all the different steps within the process. In Section 4.3, we identify the steps of the main process flow in our workshop which we use in 4.4 to make a value stream and explain all the important steps in the process to try to get an understanding of the process as good as possible. This chapter's goal is to get a better understanding of the system. Therefore, we won't directly draw any conclusions from the flow diagram/value stream. The analysis and drawing of conclusions is done in the next chapter: Chapter 5.

4.1 Factory layout

The production facility of Aerosud is really big. Aerosud has approximately 800 employees, and the production facility is split up in 8 big, so-called, "workshops". In Appendix D, an overview of the whole factory can be seen. The scope of this project will be the Vac-Form production line/the "Vac-form"-production line, which is in workshop number 1. Almost all the machines in this workshop belong to the Vac-Form production line. To get a general impression of the whole factory, I got a walkthrough with some general explanations from Mr. Tustin and Mr. Nel.

4.2 Aerosud's Vac-Form production line

In this section, we zoom in on the workshop on which we are going to focus in this project. To get a understanding of what is happening, Mr. Tustin and Mr. Nel gave me a walkthrough through the workshop in which they gave a thorough explanation of all the processes. In Workshop 1 we have a few processes that are carried out for different production lines. These processes are not part of our scope on this project. Workshop 1 also has a few machines/work cells that are completely separate from the main process in Workshop 1 and are used for different production lines. The production line which will be focused on in this research is the "Vac-form"-production line. An overview of where the different work cells are in Workshop 1 can be found in in Appendix E. In general, the production line consists of "Vac-Form" work cells that form the material in the right form using a technique called vacuum-forming, NC-trim machines that cut the material in the right shape, deburring stations to trim of all the rough edges, the paint shop, an assembly station, two inspection points, and a wrapping and packing station. Not all the products follow the process in the same sequence, but most of them do the same steps in the same sequence. In total, 287 different products are made on the Vac-Form line, which makes the Vac-Form line a job shop environment instead of a continuous flow manufacturing environment.

In Figure 8, a detailed process map is made using a flow diagram. The diagram is made broader than cell-level (for the cells that are defined by Aerosud) only: the different working cells can be seen and some extra important actions that are also part of the process. This is done to give a process flow diagram that is as complete as possible and to get a good understanding of the material flow. In the process map, you can see the different rectangular shapes that stand for different processes. The diamond shaped shapes are points in the diagram were a decision is made based on the product's specifications to determine what the next step is going to be. Before we explain all the different steps in the process, we first identify the main steps in the next section (Section 4.3). In Section 4.3, we also explain the different steps in the production process.

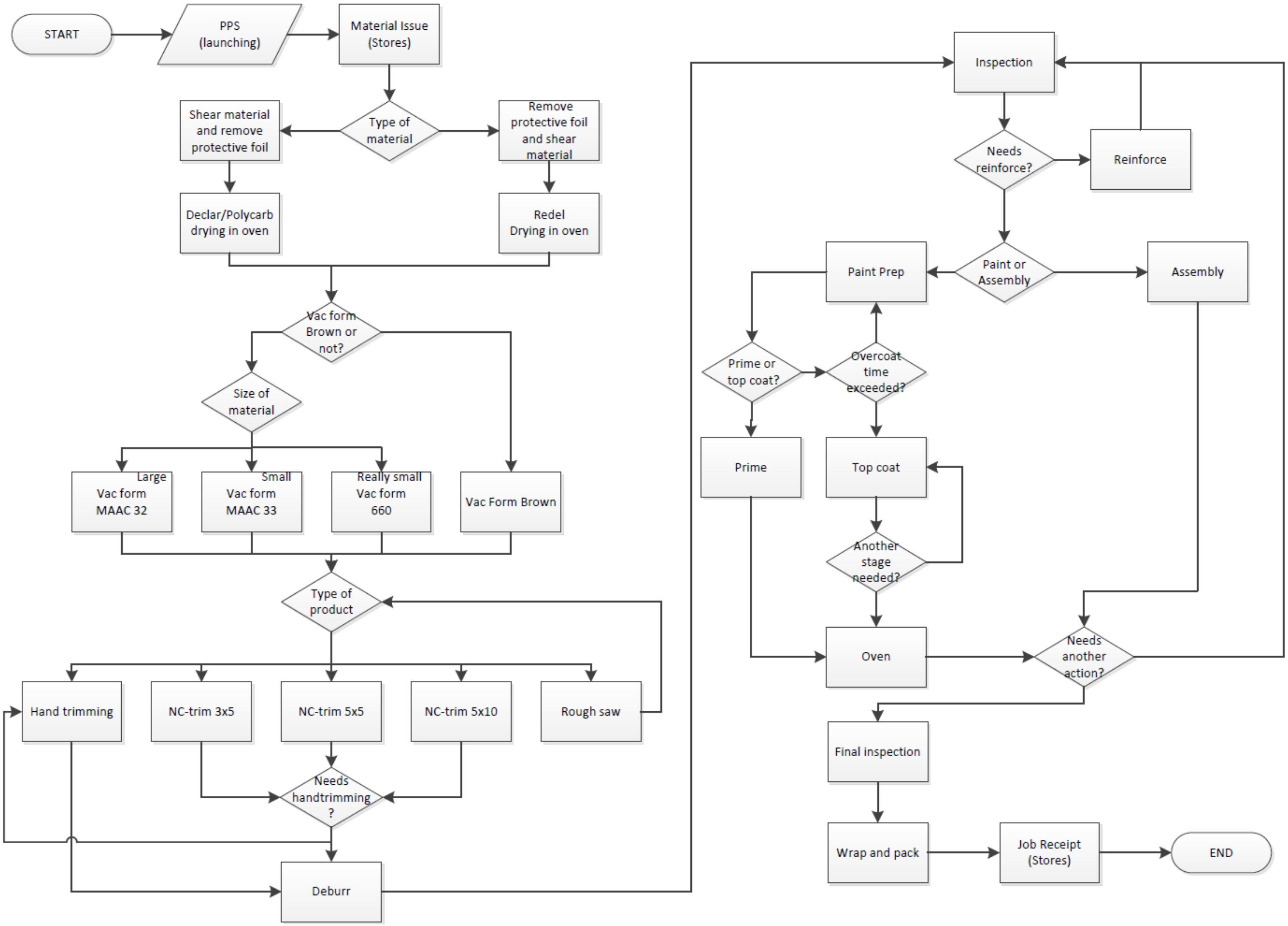


Figure 8: Production flow diagram

4.3 Main process identification

As you can see in the previous section, there are a lot of different “routes” for the product to go through during the process. Not every product goes through the same process. To be able to identify the right constraint in Chapter 5 (the first step of TOC), which we will do partly based on our VSM, we identify the process that most of the products go through. In this section, this selection and the reasons for including or excluding the process to the value stream, are discussed. The assumptions and data on which inclusion or exclusion to the value stream is based on are a result from data analysis from SFDC (Shop floor data collection-software), from observations on the work floor and from information I got by talking to employees at Aerosud.

First of all, we identify the processes that can be eliminated for the value stream. All the processes that are eliminated from the main process have a red coloured border in Figure 9. The first and main reason for excluding processes is that only a small percentage of all the products go through a certain step. This is the case with the 'Vac Form 660'. This is a small machine that is only used for the smaller parts. The total percentage of products that go through this step is really small, so that's why we won't consider this anymore in the rest of this research. The same is the case with the NC-Trim 3x5. This machine cuts the products formed by the 'Vac Form 660', so also only does a small percentage of the work and is therefore left out. Furthermore, at trimming, we have the hand trim and the rough saw that will be left out because only ±10% of the products go through these steps. Then after inspection we leave out the reinforcement. Reinforcing is only needed for a few parts while the majority skips this step. Then lastly, we also don't consider the material issue at the start and the job receipt at the end, while this isn't part of the material flow and no changes are made to the product.

The processes that are part of the main process flow are coloured green. Underneath, we discuss the different steps in the main process and what happens at the specific steps.

1. Guillotine 1
   At the guillotine, the operators receive a PPS (Process Planning Sheet). On the PPS, the operators can see which sheet material they need (Declar, Polycarb, Redel) and what thickness of sheet material they need: 60, 80, 90, 125 TY (TY is the code of a certain thickness, but can't be calculated to mm directly). The PPS also tells them how many pieces they need to cut the material in and which size it needs to be.
2. Oven
   This is a simple step that is needed to completely dry the sheets of material. After the operators at the Guillotine have cut the material in the right sizes, they put it in the oven for approximately 24 hours. After 24 hours, all the water that might have been in the material has evaporated completely.
3. Vac-Form
    a. Vac-Form-MAAC
    b. Vac-Form-Brown

   The Vac-Form work cell is the cell where the sheets of material get formed into the right shape using a vacuum form technique. The sheet material gets heated until it's hot enough to form. After that it is pushed onto the tool with the right shape, and a vacuum is created between the material and the tool to form the material in shape. In workshop 1, there are three different Vac-Forms. The MAAC 32, MAAC 33, and the Brown. The MAAC 32 and 33 are able to do the same, so in the value stream they can be considered together. The Vac-

Form Brown is different, and uses a vacuum on one side, and extra pressure on the other side, to form products in the right way.

4. NC-trim 1-1 (5x5&10)
   The NC-trim cell consists of two machines: the 5x5 and the 5x10. The NC-trim gets the products from the Vac-Forms and by using an automated machine, the product is cut out. To be cut out, the operators should put the right mould on the machine and the needed tools to cut with. For every product, the operator needs to put the product from the Vac-Form onto the mould, let the machine cut it out, and remove it from the mould. In general, the two machines can do the same, so that's also why they can be taken together in the value stream. The difference between the 5x5 and 5x10 is mostly that the 5x10 is able to move in a bit more ways than the 5x5.
5. Deburr 1
   After the products have been cut out by the NC-Trim, they go to the deburring stations, where two employees remove all the rough edges of the product
6. Inspection 1-1
   When the products have been deburred and all the edges are smooth, they are sent to the inspection station. At the inspection station, the inspector will check if all the processes have been carried out correctly: is the product formed good, does it have all the holes and forms that had to be made at the NC-Trim and is the product deburred sufficiently.
7. Paint 1 PREP
   At the paint prep station, the products get prepared for their painting (primer or top coat). The surface of the product gets treated so the paint will stay on.
8. Paint 1 PRIMER
   After Prep, the product will be painted with a primer. This is the basic layer of paint that every product that needs a paint job gets first. After the primer has been applied, the product gets into an oven to harden.
9. Paint 1 TOP COAT
   If the primer is applied, the product goes past the paint prep again. After that, it will get a top coat paint, which will be the final colour of the product. After applying the top coat the product goes into the oven again to dry completely
10. Vac-Form Assembly
    After inspection, most of the products go to the assembly station. This station has several operators, who parallel work on different product assemblies. They have to glue things on, attach metal parts, etc.
11. Inspection 1-2
    This is the final inspection. If all the steps have been done correctly, the product will end up at the final inspection, where somebody checks the crucial aspects of the product on the basis of information he sees about the product in the computer system.

12. Wrap and pack
    If everything is according to the requirements at the final inspection, the product will be put at the wrap and pack station. Here, somebody wraps the product in bubble wrap, puts tape on it and places it in a box for the completed goods warehouse.

As said before, this is the main product flow. All the products have their own specific sequence of steps. All the steps are listed on the PPS. When an operator starts working on a product, he scans the action into the SFDC system. When he finishes, it's scanned again, so the next cell in the system knows they have a new job available. All the jobs are automatically ordered based on their

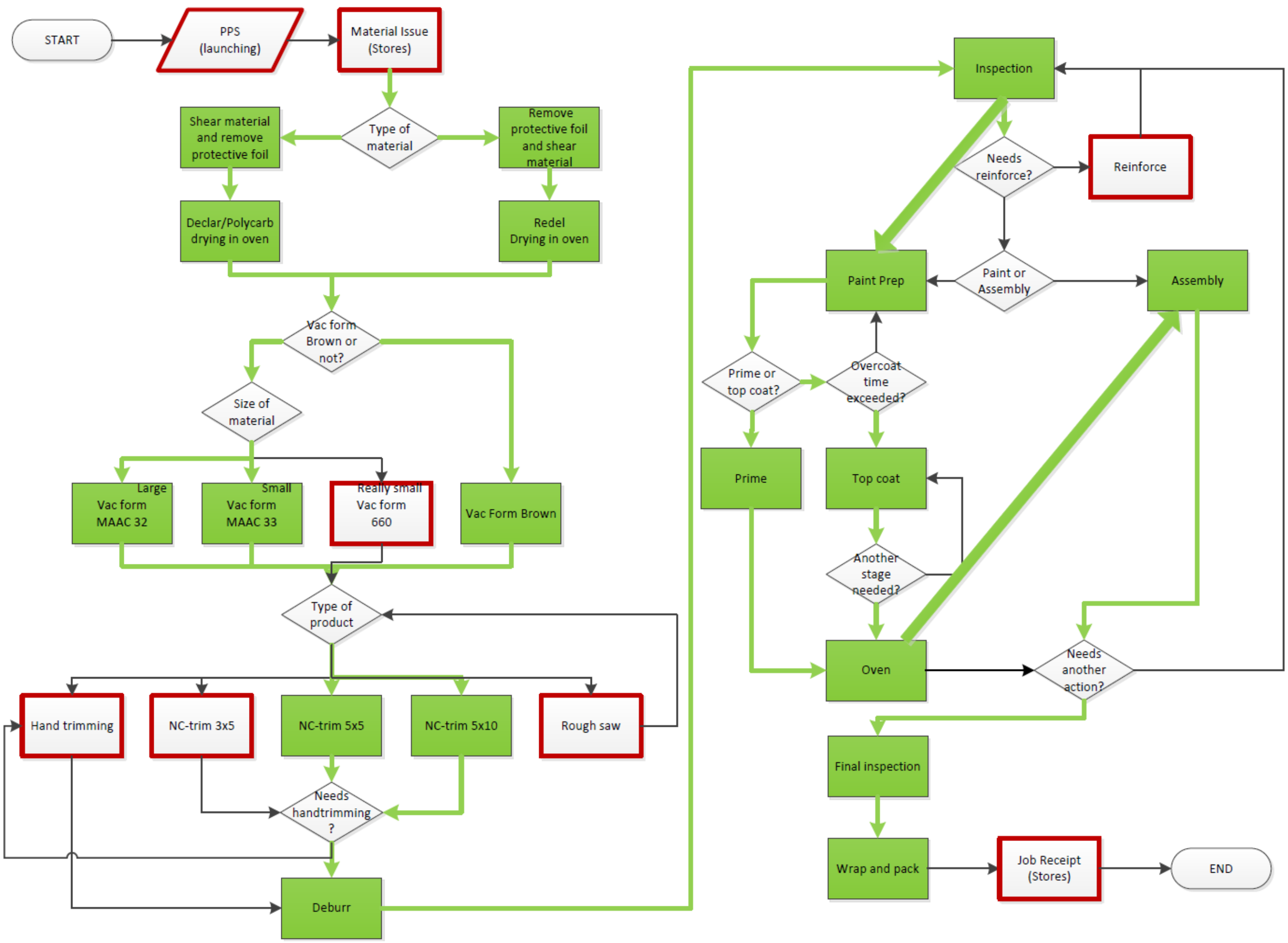
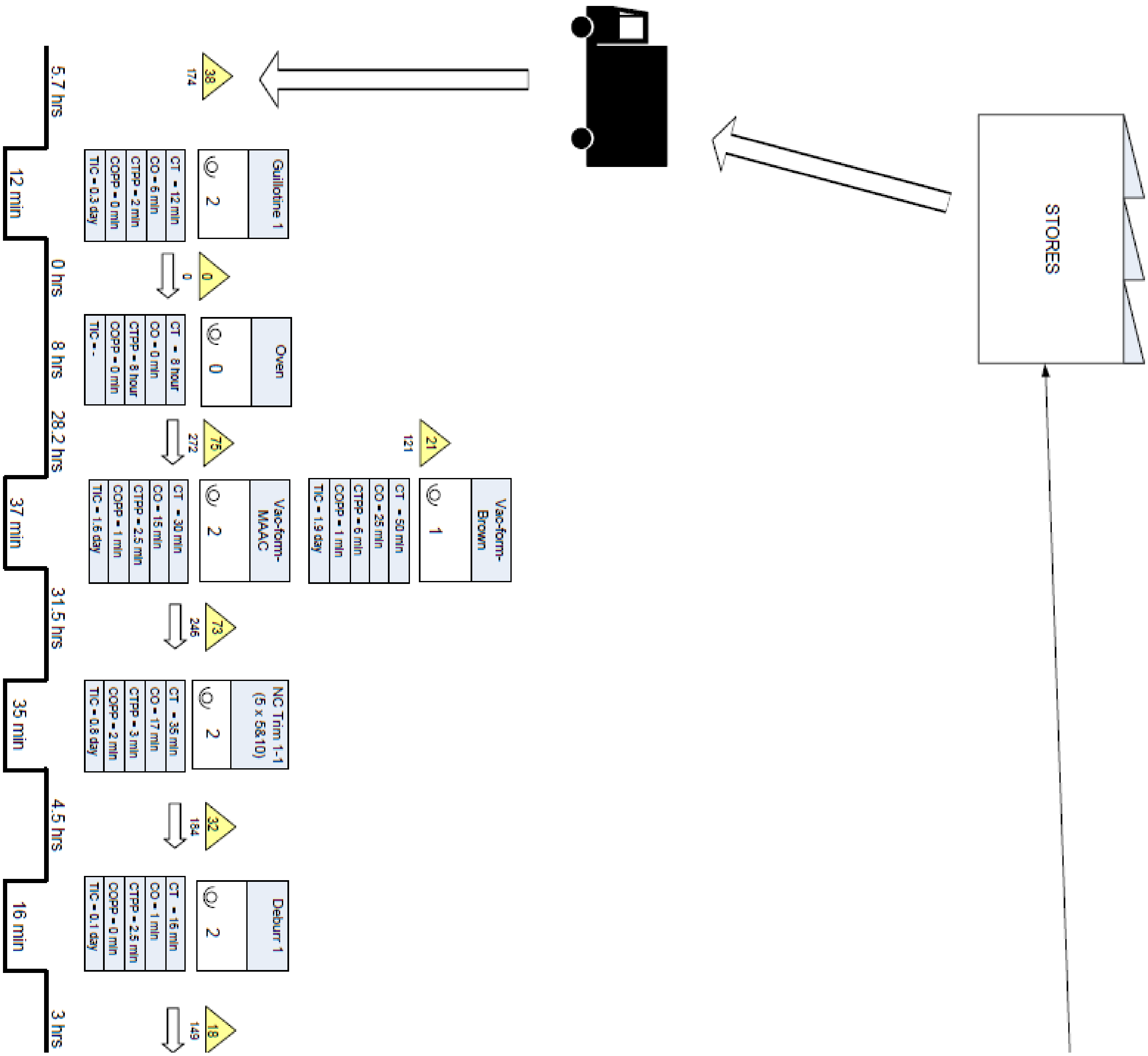


Figure 9: Main process flow

urgency, and when the operators finished a job, they always start working on the next product with the highest priority.

4.4 Value stream mapping (VSM)

The 12 steps mentioned in Section 4.3 are used to make a value stream. The Value stream has been made based on the walkthrough with Mr. Tustin and Mr. Nel, conversations with both of them and conversations with people on the workshop floor. The Value Stream of the main process can be seen below. The meaning of the things shown in the value stream can be found underneath it.



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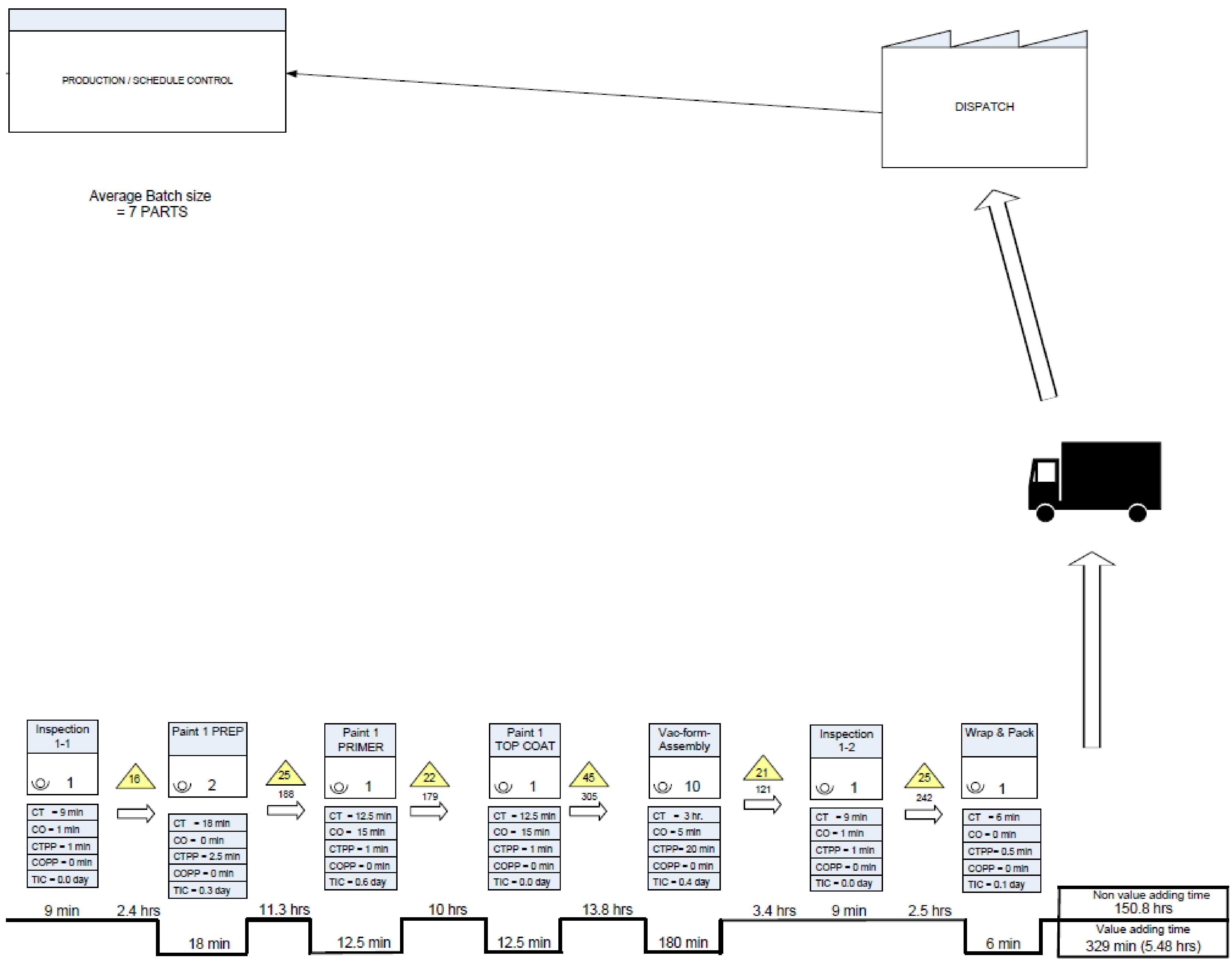
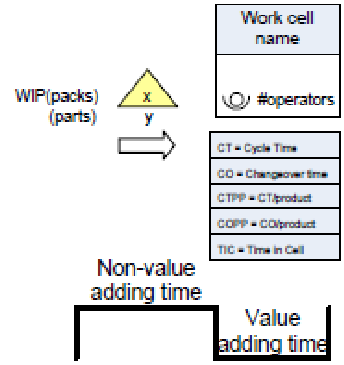

PRODUCTION / SCHEDULE CONTROL
DISPATCH
Average Batch size
= 7 PARTS
Inspection 1-1
1
CT = 9 min
CO = 1 min
CTPP = 1 min
COPP = 0 min
TIC = 0.0 day
16
Paint 1 PREP
2
CT = 18 min
CO = 0 min
CTPP = 2.5 min
COPP = 0 min
TIC = 0.3 day
25
188
Paint 1 PRIMER
1
CT = 12.5 min
CO = 15 min
CTPP = 1 min
COPP = 0 min
TIC = 0.6 day
22
179
Paint 1 TOP COAT
1
CT = 12.5 min
CO = 15 min
CTPP = 1 min
COPP = 0 min
TIC = 0.0 day
45
305
Vac-form-Assembly
10
CT = 3 hr.
CO = 5 min
CTPP= 20 min
COPP = 0 min
TIC = 0.4 day
21
121
Inspection 1-2
1
CT = 9 min
CO = 1 min
CTPP = 1 min
COPP = 0 min
TIC = 0.0 day
25
242
Wrap & Pack
1
CT = 6 min
CO = 0 min
CTPP= 0.5 min
COPP = 0 min
TIC = 0.1 day
9 min
2.4 hrs
18 min
11.3 hrs
12.5 min
10 hrs
12.5 min
13.8 hrs
180 min
3.4 hrs
9 min
2.5 hrs
6 min
Non value adding time
150.8 hrs
Value adding time
329 min (5.48 hrs)

In the value stream, we mention 5 values which contain specific information about specific work cells within value stream. The meaning of the abbreviations can be found on the right. We chose to use these 5 values because Cycle Time and Change over time are in general always used in value streams while they are interesting in all environments. We choose to include these values “per product” as well as a result from discussions with Aerosud, because this hasn’t been looked at before at Aerosud and might give some interesting insights as well. Lastly, we also included the average Time in Cell at every work cell, because this is one of the main KPIs at Aerosud, which might be very interesting later, during the constraint identification. Below, we discuss the five values mentioned and explain how the values in the value stream have been determined. In Table 4, some general information can be found about the work cells that are covered in the value stream. These values have been determined by looking at the data from 1 month. The data has been extracted from SFDC. It is important to realize that the different possible sequences that the product can go through influence the data in SFDC a lot. For example: there is an obvious loop at the part that covers the first inspection, painting and assembly. This means that products go through that inspection several times, and will also be registered in SFDC multiple times. This is important to know when interpreting the data at the cells: If SFDC says that it has processed a certain number of products on one day, then that doesn’t have to mean that all those products are unique/new products. What is also interesting in the value stream is the relatively low average batch size. This is a result from several of the same PPS’s that are put in the system with batch quantity 1 (instead of one PPS/batch with multiple products), which skews the data a lot, since PPSs like this are batched in practice. Because we know different reasons why some of the data is not directly usable/reliable, we won’t really use these values from the value stream, and they will mainly be checked for a general idea about the average values in the production line.



- **Cycle Time (CT)**
  The time that is needed to complete the production of a whole batch
  *((Cycle Time per product + changeover time per product)*number of products in a batch).*
  In Table 4 we determined a value for the average time that is needed to complete a batch. That is the Cycle Time plus the Changeover time. You would think that the CT can be determined best by subtracting the change over time from this value. However, we can’t trust these values completely, because they give a skewed image of reality since some PPSs consist of the same products, and will be produced after each other, which results in not having to do the machine changeover anymore. Therefore, we won’t use the values of Table 6. Another option to determine the CT is adding the CTPP and the COPP and multiply that by the average batch size (the formula above). This also doesn’t give a good

image of reality, since the average batch size mentioned in the value stream isn't the same as the average batch size of the specific work cells and the CTPP and COPP aren't reliable because they're estimates. This is why we also don't use this method. The best option left is to go to the workshop-floor to ask for estimations of the average CT. In addition to these estimations, we took some time samples to confirm the estimations.

- **Change Over Time (CO)**
  The time that is needed to change the machine or work cell to such a state that it can produce a different product with different specifications. CO is the time measured from the moment that the last product of a batch is finished, until the production of the first product of the new batch starts.
  The change over time has not been registered anywhere in any system, so the only option to determine this is by going to the production floor and ask the managers and operators about their best estimation about the time. Furthermore, we also do some time sampling here to see if the values needs adjustments or if we can leave them like determined based on the estimations.
- **Cycle Time per product (CTPP)**
  The time that is needed to produce one single product. The same holds for this value as for the CO: there's no data available for the CTPP. To determine the CTPP we followed the same way as with the CO and went to the workshop to ask for estimations and take time samples.
- **Change over time per product (COPP)**
  The time that is needed to prepare the machine or work cell for the production the next product (within the same batch!). The same holds for this value as for the CO and CTPP: there's no data available for the COPP. To determine the COPP we followed the same way as with the CO and CTPP and went to the workshop to ask for estimations and take time samples.
- **Average Time in Cell (TIC)**
  The average time that a PPS/batch of products spends in a work cell.
  We determine this value by analysing the data from SFDC. TIC is one of the indicators that is used at Aerosud to check the system's performance. The data available is from week 29 until week 42 (14 weeks in total). We have determined the averages of the values of those weeks, which can be found in Table 5.

As you can see, we have to do a lot of estimations (and some small time sampling) to determine the values that we use in the value stream. The main reason for this way of data collection is that certain data isn't really reliable data in combination with the time limitations we have, which doesn't allow us to do thorough time studies. It is also important to realize that the CT and the CO can't be calculated from the CTPP, COPP and average batch size, because the batch size is an (skewed) average over all the cells and that the CTPP and COPP are also rough estimations.

Table 4 : Cell specific data

	nr. of batches (1 month)	avg. batch size	nr. of products (1 month)	nr. Products per hour	nr. Products per day	nr. Batches per day	average CT+CO (min)
Guillotine 1	1025.00	6.13	6282.00	37.25	285.55	46.59	9.87
Vac-form-Brown	166.00	7.36	1222.00	7.25	55.55	7.55	60.96
Vac-form-MAAC	551.00	6.05	3334.00	19.77	151.55	25.05	18.37
NC Trim 1-1 (5 x 5&10)	805.00	4.97	4002.00	23.73	181.91	36.59	12.57
Deburr 1	597.00	7.01	4185.00	24.81	190.23	27.14	16.95
Inspection 1-1	1165.00	8.44	9831.00	58.29	446.86	52.95	8.69
Paint 1 PREP	435.00	8.84	3844.00	22.79	174.73	19.77	23.26
Paint 1 PRIMER	356.00	8.92	3177.00	18.84	144.41	16.18	28.43
Paint 1 TOP COAT	463.00	8.31	3849.00	22.82	174.95	21.05	21.86
Vac-from-Assembly	552.00	8.06	4447.00	26.37	202.14	25.09	18.33
Inspection 1-2	1131.00	4.99	5649.00	33.49	256.77	51.41	8.95
Wrap & Pack 1	1458.00	7.32	10672.00	63.27	485.09	66.27	6.94

Table 5: Average TIC of every PPS per work cell over 14 weeks (in days)

	Guillotine 1	Vac-form-Brown	Vac-form-MAAC	NC Trim 1-1 (5x5&10)	Deburr 1	Inspection 1-1
average TIC (days)	0.3	1.9	1.6	0.8	0.1	0.0

	Paint 1 PREP	Paint 1 PRIMER	Paint 1 TOP COAT	Vac-Form-Assembly	Inspection 1-2	Wrap & Pack 1
average TIC (days)	0.3	0.6	0.0	0.4	0.0	0.1

Furthermore, we also use the triangular shapes in between the processes. The numbers in these shapes stand for the WIP/Inventory that's waiting for the next step to be finished. These values have also been extracted from SFDC.

Underneath the value stream, we have a line with times (the timeline). The pieces of the timeline that are higher than the rest stand for non-value adding time in the production process. The pieces that are lower than the rest, and which are placed under the processes, are value adding steps. At the most right side of the line, you can see the total waiting time in the process (which is non-value adding) and the process time (the value adding time). These values have been determined by using the cell specific values in the value stream. The waiting time (upper parts) can be calculated by adding the CT and the CO, multiplying that value by the WIP from that work cell, and dividing that number by the number of operators at that cell. The value added time (lower parts) is simply the CT of that cell.

Important footnotes about the VSM are:

- The non-value adding time in front of the Vac-Form-Brown and Vac-Form-MAAC is the calculated time for the Brown. The non-value adding time for the MAAC is 26,1 hours. We chose to put the 28,2 hours on the time ladder in the VS because this is the "worst case" from the two. If we want to identify a constraint, or draw any conclusions from the VS about potential bottlenecks, that the worst value is the most interesting.
- The values in the value stream are mainly a result of estimations. This has to be taken into account when you use them to calculate something. When you want to do calculations with these values, you have to realize that the absolute values can't be trusted directly.
- The number of operators at Assembly is 10 in the value stream. In real life, there can be a maximum of 9 operators at this cell. But, they do sometimes get help from workers from other workshops. This means that there will sometimes be even 13 people at Assembly. In general, the cell manager estimates the amount of workers on Assembly at 10 persons. We use this value in the value stream to get more reliable data about the non-value added time in front of the cell that is needed to work out all the WIP.
- We put the WIP and the non-value added time between the Guillotine and the oven in as 0 because all the product that have been cut at the Guillotine go directly into the oven. Therefore, there is no waiting time or WIP in between the cells.
- To determine the WIP values, we used data that also includes products that belong to other production lines and which won't go through the complete process. We choose to include these products as well because these products also are products waiting to be processed, and will give a better general idea about where the problems are.
- The steps in the value stream represent the steps of the main process flow. Not all the products go through the system exactly like this.

4.5 Chapter summary and conclusion

In this chapter we've made a thorough analysis of all the steps within the Vac-Form production line. First we made a flow diagram to get to know the complete process and get an understanding of everything as good as possible. Then we identified the main process flow from the flow diagram. This is necessarily to simplify the complex process into one main process. This main process can be used in the rest of the project in for example the Value Stream. The value stream is the last aspect of this chapter, in which we made an overview of the main process with some general data about the cells.

All this is done to get a good understanding of the whole process. There haven't been drawn any conclusions from for example the Value Stream yet, because this is done in the next chapter.

The research question for this chapter is : "How exactly does the production line work?" We answered this question by making the flow diagrams and Value Stream. What we can conclude from this chapter is that the process at which we look is a very complex process in which data can be influenced by a lot of factors, which should always be considered in the rest of the process. The value stream is more or less the final product of this chapter which contains all the main steps of the process, with which we work with for the rest of this research project.

5. Step 1 of TOC: Identify

In this chapter we answer the third research question, which is the first TOC step: constraint identification. The research question that is answered in this chapter is:

How does the system currently perform and what is the system's constraint?

We answer this question in two steps. First, in Section 5.1, we analyse the current performance of the work cells within the system and identify several potential constraints. The goal of this section is to identify potential constraints and not to choose the CCR.

After that, in Section 5.2, we look at the different potential constraints that we have identified and consider all the data and information that is used to determine the constraint. On basis of this consideration, we will choose which method and which bottleneck is the most interesting to use in this project and choose the CCR for this research. The reason that we first determine the potential constraints and only after that choose the most valuable method for us is because some methods only give useful results in certain production facilities. We can't determine which method gives the best results before using the method and identifying the potential constraint. So therefore we do it in sequence.

According to the lean literature, the system's bottleneck (the CCR in TOC) is the point in the process in which the product loses value in the opinion of the customer. This can be the throughput, quality of the products, etc.. The specific value that we're striving to improve in this project is as said before On Time Delivery (while keeping Quality of the end product at the same level). In the lean perspective, a low performance in the CCR influences the customer value, the value for the customer is On Time Delivery, so the CCR must influence the On Time Delivery, and by improving the CCR, we should be able to improve the On Time Delivery.

5.1 What is the current performance and what are the potential constraints?

In this section, we give an overview on the performance of the different work cells, from which a conclusion can be drawn on what the constraint is (Section 5.2). Data has to be gathered to show what the current performance is. First, we analyse our value stream from Chapter 4. After that, we use the 4 constraint identification methods from Section 2.4.2.

5.1.1 Value Stream Analysis

The value stream that we made in the previous chapter is analysed first. To do this, we mainly look at values that stand out or other interesting aspects. In addition to that, we also search for data that are interesting to combine with the values from the value stream. From the literature we identified 2 major ways to identify a constraint: by looking at steps in the process that are non-value adding and not necessary, or by looking at high numbers of non-value added time that stand out.

The first way to identify the constraint is by looking at steps that are non-value adding, and also not necessary. In the value stream we see three steps that are non-value adding: the oven in which the products dry after being cut at the Guillotine and the two inspection points in the process. The oven is not directly value adding, but is necessary to prepare your materials for production. Therefore, the oven can't be a potential constraint. The two inspection points (inspection after Deburr and final inspection) are both non-value adding and not necessary (although these steps can be really helpful and important). The steps only take a really short time to be completed (10 min) so they probably won't cause big problems within the process, but nevertheless, we do identify the inspection points as potential constraints from this first constraint identification method on our VSM.

The second way to identify the constraint from the VSM is by looking at non-value added time. This method is really easy to use, because we can simply look at the times in the time ladder and find the highest values. The values that stand out are the 28.2 hours from the Vac-Form-Brown, and the 31,5 hours from the NC-Trim. The third highest non-value adding time is 13,8 hours at the Vac-Form-Assembly cell. Because the values for the Vac-Form-Brown and the NC-Trim are really close, it's hard to determine one bottleneck from these values, especially because there are a lot of estimations in the value stream which aren't 100% reliable, but which have a big influence on those values. Therefore, we want to look at a different way to look at these values or to do a different calculation that is based on the same principle. The main principle of this method is that we identify the cell that needs most time to work away all its WIP. Together with the data about the WIP, we also have data available on all the cells and their average throughput per day in that same period. By dividing the WIP (in products) by the average throughput (in products) per day, we get the average time that is needed to work away the average WIP of every cell. These same values are also available in terms of packs and can be found in the table below (Table 6). The value of the number of days needed to work out the WIP that is calculated in terms of parts is the most reliable data, so that's why we choose this indicator to determine our potential bottleneck. We see that there are two cells that stand out from this data: the Vac-Form-MAAC and the Vac-Form-Brown. The values of these two cells are quite close, but the values in the value stream point out the Vac-Form-Brown as one of the two cells with the highest non-value added time. Therefore, we choose the Vac-Form-Brown as the potential constraint from this constraint identification method on our VSM.

Table 6: Average time needed to work out the average amount of WIP per work cell (over 4 months)

Work cell	**WIP work away days in parts**	**WIP work away days in packs**
Guillotine 1	0.65	0.84
Vac-Form-MAAC	1.89	2.93
Vac-Form-Brown	2.37	3.05
NC Trim 1-1 (5 x 5&10)	1.29	1.65

Deburr 1	0.94	1.00
Inspection 1-1	0.37	0.37
Paint 1 PREP	0.77	0.68
Paint 1 PRIMER	1.32	1.35
Paint 1 TOP COAT	0.93	0.92
Vac-Form Assembly	1.36	1.53
Inspection 1-2	0.49	0.49
Wrap & Pack 1	0.47	0.35

5.1.2 Constraint identification methods

In Section 2.4.2, we identified 4 methods that can be interesting for identifying the constraint. In this section, we take a look at all of these methods, and use them to identify potential constraints. So all the bottlenecks that results from these methods are potential CCRs and don't necessarily need to be the final CCR. Underneath, we try to find the potential CCRs by using the constraint identification methods.

1. **The machine with the largest WIP**

The potential constraint from this method can be identified by looking at large accumulations of WIP (work-in-process) on a specific work cell on the plant floor. WIP is the number of products that have started the production process, but haven't finished it yet. Inventory/WIP often accumulates before/at the constraint. For example: If work cell 1 can produce products that are ready for the next work cell (work cell 2) much faster than cell 2 itself, then the number of products completed by work cell 1 and waiting for work cell 2 will increase and is called the WIP at work cell 2.

When making the value stream, we already identified the average WIP from the start of every day over a period of time of 4 months (in parts and packs). We see the WIP at every cell in the value stream in the triangle in front of the work cell itself and in Table 7 as well. We show the value of the WIP in packs as well as in parts. We decided to show both, because in general they more or less give the same results, which makes the data more reliable. However, this is not always the case. If we look at for example the NC-Trim and the Vac-Form Assembly, we see that one of them has the highest WIP in packs, and the other has the highest WIP in parts. This is a result of the fact that there is a different average batch size at the different work cells.

However, still with these variations/influences, we see a few high WIP (in parts and packs!) values at the cells Vac-Form-MAAC, NC-Trim and Vac-Form Assembly. We choose to let the decision (for the potential CCR from this method) depend on the values of the WIP in parts. We choose to do this, because for the value for parts, there is no influence from the fluctuating batch sizes. If we look at the WIP values in parts, then we see that the value at Assembly is considerably higher. So, for that reason, we identify Vac-Form Assembly as the first potential constraint.

Table 7: Average WIP at end of day (over 4 months)

	Guillotine 1	Vac-Form-MAAC	Vac-Form-Brown	NC Trim 1-1 (5 x 5&10)	Deburr 1	Inspection 1-1	Paint 1 PREP	Paint 1 PRIMER	Paint 1 TOP COAT	Vac-Form Assembly	Inspection 1-2	Wrap & Pack 1
WIP End of Day (Packs)	38	75	21	73	32	18	16	25	22	45	21	25
WIP End of Day (Parts)	174	272	121	246	184	149	150	188	179	305	121	242

2. The machine with frequent expediting/firefighting

The potential constraint from this method can be identified by looking for areas where some sort of process expeditors are often used. This can be seen by looking at places were people often have to get extra material or quickly have to do things to speed the process up/to keep the process going. This is often the case at the constraint to ensure that the critical orders are completed on time.

There is no data available on this in SFDC, and we are also not able to deduce it from any other data. Therefore, this method is only based on observations in the workshop and talking to people on the work floor. The people in the workshop don't have time for a real interview, so therefore all the talks are informal while they're working. To get to know how people experience it, we asked them if they have to get certain things often because it's not available or because something went wrong. At almost all the work cells, the employees told that this is not the case, and that almost always everything is on hand and that they can keep working all the time.

When talking more, we discovered several things that the workers see as normal, but that are some sort of process expeditors. This was the case at Vac-form-Brown, Vac-form-MAAC and Vac-form Assembly.

After a batch is completed at the Brown or the MAAC, some products need to be moved to a cart or to another place. To do this one by one would take much time, so it often happens that after a batch the operators of different Vac-form machines have to help each other moving a big stack of products.

At the Vac-form-Assembly cell, they said that it happens every now and then that they have to get something extra, but that it doesn't happen often. The main conclusion from the observations was: employees at the assembly cell run out of (or don't even have) tools they need for assembling products (bolts, screws, glue, etc. but also other parts that need to be assembled onto the product). It's not available in their workplace (anymore), so they have to get up to get the things they need. What is also the case at Assembly, is that employees from other workshops are asked to help out at the assembly cell. This sometimes gives 4 persons extra in manpower, which is a lot. Things like this didn't occur at any of the other cells, so that's why the combination of different observations results in that we identify the Vac-form-Assembly as the potential constraint from this second method.

3. **The machine with the greatest percentage of fail state.**

The potential constraint from this method can be identified by looking at the machine with the greatest percentage of fail state: the relative percentage of time in which the machine is broken and can't be used. A machine that is broken a lot can be the constraint of the system. The percentage of fail state is calculated by dividing the time in fail state by the total time (fail state + working state).

We have available data from April until September 2017 (6 months). During this period, most of the machine didn't have any breakdowns and had an availability of 100%. Only 5 machine(part)s in workshop 1 had breakdowns. In Table 6, you can see the fail state of these 5 machines. So, the work cells that can be the potential CCR from this method are: NC-Trim, Vac-Form-MAAC and Vac-Form-Brown. The Vac-form-MAAC has the lowest fail rate, so we don't choose that one. Then about the NC Trim and Vac-Form-Brown: we have two routers of the NC-Trim that have been broken: one of the fail rates is higher (15%) than the Vac-Form-Brown (5%), and one of them is lower (3%). The NC Router that has a higher fail state (15%) is much higher, compared to the Vac-Form-Brown fail state, so that's why we choose the NC-Trim cell as the potential constraint from this method.

Table 7: Average Machine fail state (6 months)

Cell	Machine Description	Average Machine Fail State
NC-Trim-1-2	NC Router 5 X 5	**15%**
NC-Trim-1-2	NC Router 5 X 10	**3%**
VAC-FORM-MAAC	Maac Vacformer 32	**2%**
VAC-FORM-MAAC	Maac Vacformer 33	**1%**
VAC-FORM-BROWN	Brown Vacformer	**5%**

4. **The machine with the highest utilization (using Throughput Accounting).**

With this method we want to identify a potential constraint by looking at the utilization of the machines or work cells in the production line. The machine with the highest relative utilization can be the system's constraint. The machine utilization is calculated by dividing the practical by the theoretical capacity of the machine. The practical capacity is the capacity that is needed to produce all the products that are demanded. The theoretical capacity is the capacity that is available to use on that that specific machine or work cell.

In Appendix B, you can see an example on how to determine a potential CCR using Throughput Accounting. On the first two pages, we discuss the different terms and their definitions. To make it more clear, we also show an example on how the simplified throughput accounting works. On the third page, you can see which values are needed for the calculation of the Resource Load percentage and how all the needed values are calculated. The definitions of all the terms can also be found in this appendix.

The excel document with all the data that is used can be found in Appendix F. This is data that was originally obtained by the continuous improvement team of Aerosud. It is important to know that all this data is based on rough estimations and not for example on accurate time studies. This can skew the final answer in absolute values, but since all the data is gained in the same way and with more or less the same deviations, we are still able to draw conclusions from the final outcomes at the end. We choose to use this data, because it is very hard to get more reliable data than this in a really short period of time. So, the available data is the best option to use to get an indication for a potential constraint from this method.

To determine the values of the productive capacity, we identified the policies, set-ups, breakdowns and maintenance. The policies include all the weekends, public holidays and days off. This comes down to 123 days in total per year. The maintenance and the breakdowns have been extracted from the maintenance data sheet. The data that was available was data for 6 months, so we took this value times two to give a better indication about the total maintenance per year. The set-up time is a result from a time study that has been done earlier which was mentioned earlier. We also choose to use this data because the time that is needed to do a time study is too much for the scope of this project. That's why we will use this general data that is already available. With this data, we can determine the Productive Capacity of all the cells. The Protective Capacity is not a fixed percentage and can be chosen by the people that carry out the research. In this case we choose to use a 10% Protective Capacity because this is used by Aerosud for simple calculations like this often and is also a really commonly accepted percentage in general. By subtracting the Protective Capacity from the Productive Capacity, we determine the Net Capacity. Then we only need to determine the Net Load for every cell. Somebody at Aerosud already did a project in which all the different stock codes were put together in certain families. Per family/group, the demand in products and the time that is needed for one product was determined, which we can use to determine our net load, using the calculation that can be found in Appendix B. In Table 8, we see the final result with the Resource load in percentages that has been calculated using the data that was mentioned above. In the last column we put in a re-evaluated resource load. This load is a result of dividing the resource load by the number of operators if there are more than 1 operators at a cell. We see that the load on the Vac-Form-Assembly is extremely high, and the only cell with too much load (>100%). Therefore we identify the Vac-Form-assembly cell as the potential constraint from this method.

Table 8: Work cell load using Throuhput Accounting

Cell	Prod. Cap. (Days)	Net prod. Capacity (Days)	Net Load (days)	Resource Load	Re-evaluated resource Load
Guillotine 1-1	241.5	217.4	172.9	79.5%	39.8%
Vacform Brown	206.2	185.6	94.4	50.9%	
Vacform Maac	187.4	168.7	122.0	72.3%	36.2%
NC Trim 5x5 & 5x10	210.3	189.3	214.2	113.2%	56.6%
Deburr	242.0	217.8	177.7	81.6%	40.8%
Inspection 1-1	242.0	217.8	76.8	35.2%	
Paintshop 1	233.5	210.2	473.3	225.2%	75.1%
Vac-Form Assembly	242.0	217.8	5744.5	2637.5%	263.8%
Inspection 1-2	242.0	217.8	32.3	14.8%	
Wrap & Pack	242.0	217.8	62.9	28.9%	

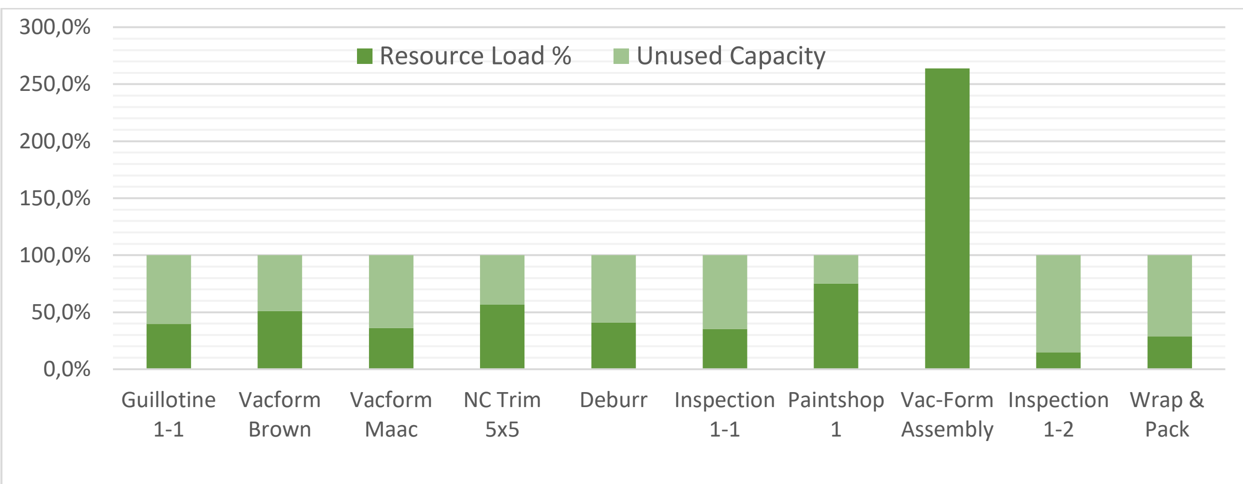


Figure 10: Resource load per work cell

5.1.3 Conclusion

So, in Section 5.1.1, we did a value stream analysis, in which we found 2 potential constraints: the inspection points, and the Vac-Form-Brown. In Section 5.1.2 we used 4 different methods to identify the potential constraint. Using these 4 methods, we identified the NC-Trim one time, and the Vac-Form Assembly 3 times. In this analysis we just used our ways to identify a potential constraint to get an outcome for every method. We can't just choose the CCR by looking at which cell pops up most because we didn't evaluate the outcomes from the methods in this project yet on their reliability or impact. An overview of all the constraints that were found can be seen below. It is important to evaluate these outcomes before we choose the CCR. This evaluation is done in Section 5.2.

Constraint identified by looking at ….	**Potential constraint**
Value Stream Analysis	
1: non-value adding steps	Inspection points
2: non-value adding times	Vac-Form-Brown
The 4 constraint identification methods	
1: largest WIP	Vac-Form Assembly
2: frequent expediting	Vac-Form-Assembly
3: greatest fail state	NC-Trim
4: highest resource load	Vac-Form-Assembly

5.2 How reliable are the chosen potential constraints?

In the previous section we identified several potential constraints. To determine them, we did a value stream analysis and we used the four constraint identification methods. In this section we evaluate the findings of the previous section. On the basis of this evaluation we are choosing the actual constraint. For this evaluation, we look at the data and information that is used for the calculations to determine the reliability of those calculations. We also look at possible factors that could have influenced the data to see how reliable the actual data is. It is important to do this because a constraint identification method isn't always perfect for every situation. This can also be seen in our evaluation. The evaluation of every outcome of the methods from Section 5.1 is based on reliability of the data, and expected impact on the system. The "score" of every outcome on these two points will is expressed in a +, 0, or – (where + means good indication for the CCR, 0 means neutral and – means bad indication for CCR).

In Section 5.2.1, we first look at our potential CCR identification from our value stream analysis. In this section, we look at the outcomes from these methods, and determine their value for this project. After that, in Section 5.2.2, we look at the 4 constraint identification methods and also evaluate the outcomes of these 4 methods and their value for this project. Eventually, in Section 5.3 a table with the scores on the two points mentioned above (data reliability and expected impact on the system) can be made to give a clear overview for our final CCR identification (Table 10). Also, an explanation on the choice that we make for our final constraint is given in the conclusion. The potential constraints and their "runner ups" that have been identified in Section 5.1 can be found in the Table below (Table 9).

Table 9: Potential constraints from using different methods

Constraint identified by looking at ….	Potential constraint	Runner(s) up
Value Stream Analysis		
1: non-value adding steps	Inspection points	-
2: non-value adding times	Vac-Form-Brown	Vac-Form-MAAC
The 4 constraint identification methods		
1: largest WIP	Vac-Form Assembly	Vac-Form-MAAC & NC-Trim
2: frequent expediting	Vac-Form-Assembly	-
3: greatest fail state	NC-Trim	Vac-Form-Brown
4: highest resource load	Vac-Form-Assembly	-

5.2.1 Value stream analysis

1. **Non-value adding steps**

The identified potential constraint are the inspection points. The information that was used to determine this is very straightforward and therefore reliable. Therefore, we score the reliability of this data a '+'. However, we also see that the inspection points only take a very short time to complete a batch. This step doesn't really add value, but it does take out low quality products, which is also very important for Aerosud. So if you look at the time that is "wasted" in this step, you could consider it as pretty much, but since the impact of the step is really important for the company, the decision wouldn't be a really good improvement for the system. Therefore, we don't consider the inspection points as cells with a really big potential impact, which makes this method less interesting for this research, and that's why we score the impact on the system a '–' for this method.

2. **Non-value adding times**

The identified constraint (Vac-Form-Brown) is identified on basis of the times that are mentioned in the value stream. These values aren't extremely reliable, so for that reason we chose to also look at the average values of the WIP in combination with the throughput. Combining the data of WIP and flow is based on the same principle as looking at non-value added times, but the data that we use here is more reliable because it is historical data over a long period (4 months). By using this data, we identified the potential constraint with reliable data, making this an interesting potential constraint. However, we do have to take into account that the firefighting at Assembly (placing extra operators in the cell sometimes) gives a higher value for the throughput. If Aerosud wouldn't do this type of expediting, then we might see a higher value at the "WIP work away days"-value. For the combination of these two things we score the reliability of the data a '0'. Making a change in the non-value added times in practice means lowering the WIP at some cells. Changing this would only be an improvement in the Operational Expenses for that single moment but wouldn't give a continuous improvement that improves the On Time Delivery. Therefore, we also score the expected impact on the system a '0'.

5.2.2 The 4 constraint identification methods

1. The machine with the largest WIP

The constraint identified from this method was the Assembly cell. Two cells that were close as well were the Vac-Form-MAAC and the NC-Trim. These two cells have a high WIP value because other production lines produce some products in Workshop 1 as well. A certain part of this WIP will leave the system after those cells. Therefore these two cells aren't really reliable as potential constraints. All the products at the Assembly cell are products that go through the complete Vac-Form line. This is the reason that for the scope of this project, in which we focus on the Vac-Form line, the Assembly cell is a really interesting potential constraint and the reliability of that data is scored a '+'. The WIP that's in the Assembly Cell is all WIP that should be handled and will cause a problem for the system if the value is too high. Therefore we also score the impact on the system a '+'.

2. The machine with frequent expediting/firefighting

The identified constraint using this method is the Vac-form-Assembly. This decision is based on our own observations and the observations of others. The reasons to choose for this potential CCR are clear, but there aren't a lot of reasons to choose this specific one, neither is reasoning very convincing. This is the reason that we will consider this as a potential constraint, but the score on data reliability is only a '0'. The impact on the system is actually really big. It often happens that >30% of the artisans is a "firefighting artisan", which means that if these people would be left away, the impact on the system will be huge. The score on impact on the system for this method is therefore a '+'.

3. The machine with the greatest percentage of fail state.

What stands out from the values at Table 6 is the 15% fail state at the 5x5 router of the NC-Trim. This is a lot, and the main cause of this high percentage fail state is that in one month, in which the machine has been broken 69% of the available time in that month. If we take this high value out, then still, we have an average fail state of 5%. So, after "making" the data more reliable, we still see the same result. Anyway, the values of the fail states isn't really reliable so the score on reliability is a '0'. Most of the machines work all the time and the machines that do break down don't have a really high fail rate, so the impact of the system is considered a '–'.

4. The machine with the highest utilization (using Throughput Accounting).

By using Throughput Accounting, we determined that the Assembly cell is the potential constraint from this method. As you can see, it has a really high value (too high). This is a result from the data that is used to determine the net load for every work cell. The times used in this data sheet are all estimations combined with some time sampling. In reality, this data could be quite different, so that's why we can't conclude anything from the absolute percentages of resource load. However, if we look at it relatively, the indication that the data gives is actually reliable. Because the indication that the relative values give is reliable, we score the reliability of this data for this method a '+'. We see that the relative difference in resource load is really big for the Assembly cell. That's why we still see the assembly line as a quite reliable potential constraint from this method. Since the relative difference is so high, we can be quite sure to say that the load on the Assembly cell is too much to handle. Therefore we score the expected impact on the system a '+'

5.3 Conclusion: What is the system's constraint?

Constraint identified by looking at ….	***Potential constraint***	***Reliability of the data that is used***	***Expected impact on the system***
Value Stream Analysis			
1: non-value adding steps	Inspection points	+	–
2: non-value adding times	Vac-Form-Brown	0	0
The 4 constraint identification methods			
1: largest WIP	Vac-Form Assembly	+	+
2: frequent expediting	Vac-Form-Assembly	0	+
3: greatest fail state	NC-Trim	0	–
4: highest resource load (using TA)	Vac-Form-Assembly	+	+

Table 10: score table of the outcomes of the different constraint identification methods

Three of the six methods say the potential constraint is the Assembly cell. The methods that tell us that the assembly cell isn't the potential constraint are the two methods from the value stream analysis, and the method that looks at the fail state of every cell. The first VSM analysis method looks at non-value adding steps, so it's logical that the Assembly cell doesn't result from this method. The inspection points are considered less interesting in the previous section, so they are not the system's constraint. The second VSM analysis method: the "non-value adding time"-method says the Vac-Form-Brown is the potential constraint. The data to determine this constraint is slightly skewed for the assembly cell, which makes it seem like there's no problem at the Assembly cell. This is mainly a result from the expediting in the assembly cell (which is also the reason that Assembly was identified as the constraint from that method). The method that looks at the fail state doesn't say the assembly cell is the potential constraint. But, if the cell with the highest fail state isn't the system's constraint, then that doesn't need to be a problem for the whole system. Therefore, we don't let this method have a big impact on our final constraint identification.

The methods that tell us that the potential constraint of the system is the Assembly cell are all considered as quite/really reliable methods, based on reliable data (Section 5.2). Especially the method that focusses on the WIP and the method that uses Throughput Accounting to determine the potential constraint are really reliable. These methods both point at the Assembly cell as the potential constraint and have a big expected impact on the system. Therefore we choose the Vac-Form-Assembly as the system's constraint (the CCR!).

6. Step 2 of TOC: Exploit

In this chapter we answer the fourth research question, which is the second TOC step: exploiting the constraint. The research question that is answered in this chapter is:

How do we want the system to perform and how can we improve the constraint?

In Chapter 2, we made our own model that contains different tools, techniques and principles that we use in this chapter to exploit our constraint. In Chapter 5, we have determined that the constraint of the system is the Vac-Form Assembly work cell. Therefore, this step is focussing on the Assembly cell and the possibilities within this cell to improve its performance.

The outline of this chapter can be split up in three parts basically: the detailed cell description (Section 6.1) in which we analyse the cell in a general way, the problem analysis (Section 6.2) in which we look at improvement possibilities and the solution generation (Section 6.3) in which we make suggestions on possible solutions. Finally, in Section 6.4 we write a brief chapter conclusion in which we briefly look at the three measurements as well. The problem analysis and solution generation are based on tools, techniques, and principles that we've identified in Chapter 2. Those are:

- Kanban / Visual management
- DBR (focus on the drum: the CCR)
- Poka-Yoke (CCR focus)
- Kaizen (CCR focus)
- 7 wastes (TIMWOOD)
- SMED (CCR-focus)
- The three measurements to check your solutions (Throughput, Inventory, Operational Expenses)
- Current reality tree

The tools/techniques and principles mentioned above aren't all tools that we can use directly for this chapter. Some of them are principles and should be used more as a general idea during this step: DBR with focus on the drum basically says that we have to realize that the Assembly cell has to determine the speed of the whole production line and isn't really a tool or something that we can use for the solution generation. The three measurements for checking solutions aren't really a tool either, but can be used like a tool to determine for every solution if it's a good solution or not.

That leaves us with Visual Management, Poka-Yoke, Kaizen, 7 Wastes, SMED and the Current reality tree as real tools that we can use. Kaizen is very broad. The main focus is eliminating waste and standardizing process steps. We already cover waste with the 7 wastes, so with Kaizen, we will focus on Standardizing (part of 5S). A current reality tree is especially useful for the assembly cell analysis. We can use this to identify problems within the cell, which we can use as a basis for the solution generation part, in which we will use Visual Management, Poka-Yoke, 5S (mainly standardizing), 7 wastes and SMED.

6.1 Detailed Assembly-cell description

In Figure 11, you can see the layout of the Assembly cell. The cell that is shown contains 9 work benches. In a different part of the workshop there are some extra work benches that are sometimes used as process expeditors and that don't belong to the standard assembly cell set up.

We first briefly discuss what's included in the work cell:

- Tool rack: rack for all the tools, shop aids and jigs that are used during the assembly to make assembling easier. After the products are finished, the tools are put back in the tool rack.
- Incoming WIP trolley: trolley where all the incoming WIP is placed. These are all the products that have finished other steps and now need assembly.
- Parts/foam parts: two racks where foam, metal, and plastic spares are stored which are used to assemble on a product. The spares are put in a plastic bag with a paper that says which PPS the spares belong to.
- PC: there are two PCs in the assembly cell. Both PCs have the same function: workers can scan their PPS in or out of the system or workers can check the work instructions for the specific batch that they're working on.
- Trolley and work bench: there are 9 trolleys and work benches in this cell. Every bench belongs to one worker, working on one batch. The trolleys are used to place the products on that aren't handled at that moment. At every bench there are several tools available that must be used for assembling products.
- Floor stock rack: the place where all the small rivets, washers, studs, nuts, nutplates, screws, screwcaps, bolts, etc. are stored. Workers can get the stock they need for their batch here. These small parts are called Aircraft General Spares (AGSs)
- Rivet press: the machine that is used to fasten the rivets.
- Matrix: a closet with drawers that contains all the AGSs. When the AGSs are finished in the floor stock rack, then the cell leader will get the AGS's from the matrix. The matrix sends a message to the stores as soon as it runs out of anything, so that it can be refilled.

The incoming WIP will come in laying stacked on a trolley which is put in front of the tool rack. To make sure that the people can start working on a batch after they finished another one, the cell leader tries to always place a next batch at the trolley of an assembly worker/artisan. If the artisan is finished with a batch, he picks the PPS of the next batch, scans it into SFDC, looks at what is required for that batch and gets the tools, jigs, consumables and AGSs that are needed to assemble that batch. Sometimes, there will be no next batch ready to be processed, so the artisan has to look in SFDC himself to decide which batch will be produced next. When a batch is finished, the artisan moves all the parts to a different trolley to bring them to the final inspection. The artisans that work “in the back” of the assembly cell think it’s not convenient to roll a trolley to their bench to place the products on, so they usually bring them to final inspection by hand.

There’s a high variation in production time per batch. Some batches can be finished in a few minutes, while there are also a lot of batches that take a few hours.

Deciding which batch should be produced next is in most cases done by the cell leader. The cell leader will make a decision mainly based on the system priorities, while the throughput per day and the TIC of products also plays a role in this decision. The system priority is split up in 5 colours: black, red, yellow, green, and blue, where black means too late, and blue means too early. The colour codes are generated by the system, based on the delivery deadlines. Within black, there is a manual system, where numbers indicate the “blackness”/urgency of the cell, ranging from -1 to -20, where -20 means that a product is really late. These manual priority numbers are decided based on the general performance for every customer. In practice, most of the packs in the system are “black packs”, making the numbered priority system the leading system priority. However, the focus is not only on this priority. The cell leader and the artisans also look at throughput per day and at how long products have been in a certain cell. They want the cell to have enough throughput per day, so sometimes they will leave high priority/long processing time batches to work on low priority/short processing time batches. They also focus on packs that have a high Time In Cell, because that’s one of the KPI’s on which they are measured. In theory, they should only push the pack through the cell with the highest TIC every day, but in practice the next batch that should be produced is determined based on priority, throughput rate and TIC values.

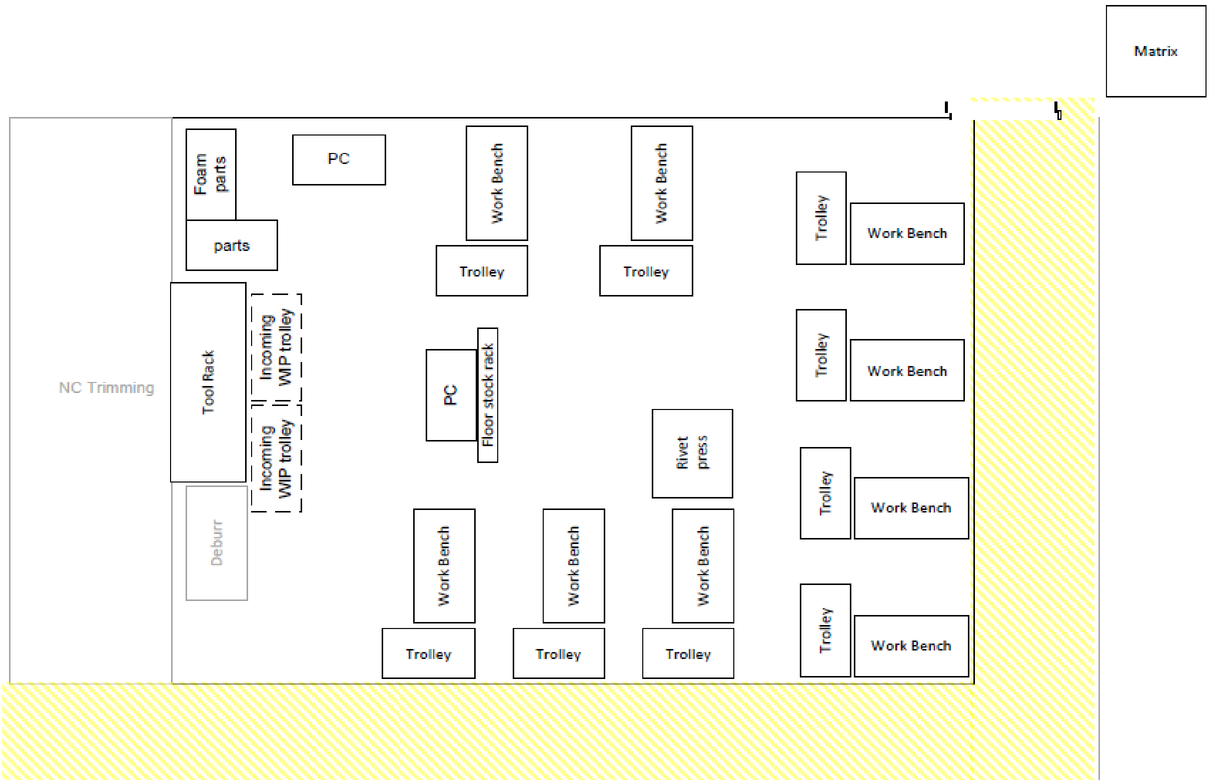


Figure 11: Assembly Cell lay-out

6.2 Assembly cell analysis

In this section we analyse the problem using the current reality tree and the tools that were identified before. We start with the current reality tree to get a better idea of general problems that occur within the work cell (Section 6.2.1). After that we want to use the tools to think of possible solutions. To be able to draw conclusions more easily we first do a time and motion study in the work cell (Section 6.2.2). After the time and motion studies, we use the lean tools to analyse the cell and to see if we see certain things that go wrong (Section 6.2.3).
The goal of this section is to analyse the work cell and find improvement possibilities or parts of processes that can be improved. This section doesn't focus on providing the solutions for those improvement possibilities. The solutions are covered in Section 6.3. All the information in this chapter is gained by talking to the artisans and cell leaders in the workshop and is a direct result of those conversations in combination with our own observations.

6.2.1 Current reality tree

In Appendix G, you can see the current reality tree that shows our main problem with its core problems/causes. This current reality tree has been made by observing the processes in the assembly cell. We also talked to the artisans and the cell leader to find out more about problems in the cell. Some causes are hard to solve (e.g. high variety in different kinds of products). Others are easier to improve. The main things that can be improved that result from this current reality tree and which can also be seen in the appendix that shows the current reality tree are:

- Workers have to do preparation for their own batch and search for things while working on the batch.
- Workers "upstream" start batching packs which causes waves of workload in the Assembly cell. (upstream cells are cells that are in front of the assembly cell)

If we look at these two main findings, we can easily divide them between the TOC steps. The first improvement possibility is the biggest problem, because this is something that happens all the time and is a standard working procedure. This is typically a problem within the Assembly cell itself and can therefore be solved in step 2 of TOC: Exploit (this chapter). The second problem is in comparison to the first problem not that big, because it happens every now and then, and it isn't a standard working procedure. This is typically a problem that is caused somewhere in the production chain before the CCR: non-CCR. The non-CCR improvement possibilities belong to step 3 of TOC: Subordinate (Chapter 7).

6.2.2 Time and Motion studies

To get a better idea of what is happening in the Assembly cell and about what things can be improved, we do a time and motion study. From this time and motion study, we measure the time from the start of the production of a batch for ±15-30 min. We write down all the movements and visualize this in a so called Spaghetti diagram, that can be found in Appendix H. During the time and motion studies, we obviously observed and saw some interesting things. Some things were only small and not that important, and by discussing all the conclusions and observations with Mr. Nel and Mr. Tustin, we came up with a list of main findings. The main findings can be found below. During the time and motion studies we also did some extra general observations which have also been taken into account while writing down these main findings. For every point that has been written down we try to estimate their impact on the system. These values have also been determined together with employees at Aerosud:

1. The artisans are walking a lot, which takes around 5 to 10% of their total time.
2. The artisans spend relatively much time at tool racks etc., because they have to search for the right thing, for a single batch, this can already take up to 5% of the production time.
3. The matrix or floor stock rack runs out of stock causing the artisans to refill them themselves. Therefore, they have to go to the stores, for which they have to walk quite far. The exact impact of this action on the system is hard to estimate, but is part of the 5 to 10% time loss mentioned in the first finding.
4. Artisans borrow tools from each other, which causes ineffective working and frustrations. The impact in time that is wasted is not really big, but it does have a negative impact on the people on the work floor.

5. Artisans have to get their own batches to work on and when finished they have to bring it away themselves. This also takes up to 5% of their working time.
6. Sometimes it's hard to determine which batch should be produced next, because there are a lot of job stoppers (other parts and spares that are needed for the assembly, but aren't ready yet). At some moments, the number of packs that have a job stopper in the cell is almost one third of all the batches. The direct effect of this is hard to determine, but since the job stoppers in the system often have a really high priority, we can assume that the impact on the system is considerable.
7. Only the cell leader and people "above" him know how the cell is performing, but the artisans don't really have any indication of this. It is not possible to estimate the impact of this on the system

The first observations and conclusions are all covered in this chapter. The last observation, about the job stoppers is a typical problem that's caused outside of the CCR-cell and is therefore discussed in the subordination phase.

6.2.3 Cell analysis using lean tools

We use our 5 tools that we identified in Chapter 2 to look at improvement possibilities. The five tools are: Visual Management, Poka-yoke, 5S (mainly standardizing), 7 wastes, and SMED. In this section we only look at the improvement possibilities that result from using the lean tools. In the next section (Section 6.3), we describe the possible solutions that result from using these tools. Below, we briefly describe in which way every tool can be used specifically within the Assembly cell. Behind every tool, we will mention the number of the problem that we mentioned in Section 6.2.2 that is solved using that tool.

Visual management (6, 7) is interesting to use in this facility to visualize the performance of the cell. In the current situation, only the cell leader (and the people above him) really knows how the cell is performing. The artisans in the cell just do what they're told to and that's basically it.

Poka-Yoke (3,5) is already used a lot within the cell. Poka-Yoke is the final step of standardization and is about striving to a situation where something can't go wrong. The 2 steps of standardization that precede making a process failsafe are visual help and visual guidance. For a lot of products there are several shop aids that have been made. For example: a shop aid makes sure that they can only sand and glue the part of the product that is needed, and can't damage the rest of the surface. The only thing that isn't "fool-proof" yet is the system that is used to pick the next batch that will be worked on. In some cases the cell leader places a batch at the work bench, but in some cases the artisan also has to get a new batch himself. In this way the artisan must make the decision about what is important to do. While the artisan doesn't have all the knowledge that is needed to make this decision, he might make a wrong decision, which the cell leader would not have made.

5S (2,4) is already implemented in several ways. For example: the tool boards have tools drawn on them to quickly see what's missing, and there is a clear system on where which AGSs can be found. There are, however, some things that could be standardized even further. This is the case for the system that's used for picking the next batch (as described above) or for preparing batches. As it is now, the artisans have to get a lot of the things that are needed for assembling a batch themselves. It would be easier if that would be standardized further, so that they don't have to spend too much time on that.

7 wastes (1,2,3,5,6): if we look at the 7 wastes, the main things that stand out is the motion and waiting within the work cell (the waste in terms of motion can also be seen from the time and motion studies). The other wastes (Transport, Inventory, Overproduction, Over processing and Defects) are all mainly eliminated and don't really have an impact on the cell. The waste in waiting is mainly a result from the so called "job stoppers". The job stoppers cause packs to be waiting in the cell, because they can't be produced yet.

SMED (1,2,5) within the Assembly work cell should focus on the change over time between batches. In principle, the assembly cell doesn't really have change over time for changing tools etc. However, we do see that there is often quite a lot of time between finishing the last part of a pack and starting the first part of the next pack. This mainly has to do with activities as searching for tools for the next pack or moving the finished goods from their work bench to the inspection area.

6.3 Solution generation

In this section we look at solutions for the improvement possibilities that we've found in the previous section. We do this based on the tools and methods that we have identified before (Chapter 2). The outline of this section is also based on these tools. We generate solutions based on the improvement possibilities from Section 6.2.3. In this section we already had some overlap in things that causes the problems. While thinking of solutions, we also realized that some of the solutions are a result from several tools/methods. Therefore, we made a matrix in which the different solutions are placed, so we have an overview of which solution resulted from which method(s). the solution matrix can be found in Table 10. Underneath the solution matrix, we describe the solutions that were found and check them with the three measurements that were identified before.

Table 10, Solution matrix

suggestion	**1**	**2**	**3**	**4**	**5**	**6**
VM						x
Poka-Yoke			x		x	
5S		x		x		

7 wastes	x	x	x		x	x
SMED	x	x			x	

1. Pre-kitting everything that is needed to assemble the part: now, only the spares are kitted at the stores and put in a plastic bag that is placed in the spares rack in the assembly cell. After that, the artisan has to look for those parts and everything else that is needed. He has to get all the AGSs, tools, consumables, etc. and once he has all that, he can go to his work bench to start assembling the products. When the artisan already has all of that at his work bench before he starts the batch, then the time needed to change from one to another batch will drastically decrease. This improvement will increase throughput.
2. Cell leader should bring the batch that should be assembled next to the work bench and bring the finished goods to final inspection. This will also increase throughput.
3. Extra accessory should be bought to prevent the time that is wasted during the production of a batch. There are extra jigs needed, extra tools (that have to be at the workbenches), extra alcohol bottles and tape holders. This will also improve throughput.
   Of some tools/jigs only 1 piece is available, while this jig has to wait until the glue is cured for a few hours for every product. The jigs that are needed are:

   - 232T1477-67
   - 232T1467-34
   - 232T1477-20
   - 232T1477-57
   - AJ214W1207-20
   - AJ214W1207-19
   - AJ232A1631-11
   - 232A1631-10TI

   Other things that are needed for the work benches that people often have to borrow them from other work benches are:

   - 92 gun (glue gun): 2 available, 9 needed
   - Normal drill: 7 available, 10 needed
   - Tape holders/dispensers: at least 9 needed (for every work bench
   - Extra bottles for alcohol

4. It should be decided per product(family) which time is available for the production of the batch. Currently there are no times for every batch, so it can’t really be seen if somebody

is working fast or slow. The real effects of this solution are hard to determine, but it will probably increase throughput.

5. Artisans should only work on the batch that is put at a work bench by the cell leader, and they shouldn't be able to pick the next batch themselves. For this to work, there also have to be clear rules for everybody about what the priority policy is. Currently, people interpret this differently. The rule "one high TIC-pack and for the rest only priorities" should be followed by everybody. This will increase the throughput *of important packs*. The throughput itself won't change that much, but by improving the throughput of the important packs, the On Time Delivery will be improved, which is the most important thing.
6. There have to be clear indications on how the cell is performing with important KPIs (e.g. the time that is worked on the products compared to the time that is available for that specific product). If this is visualized within the cell, then people will also see how they are performing and if they maybe have to work faster. The real effects of this solution are hard to determine, but it will probably increase throughput.

6.4 The three measurements + chapter conclusion

So, if we look at what is improved with all these solutions we can conclude that they all focus on improving the throughput in general or improving the throughput of important parts. The Operational expenses don't seem to be a real problem in Aerosud, and lowering the Inventory doesn't make sense yet because the results of the solution need to be seen in practise first (e.g. removing "bubbles" of workload from the system. Using the solutions mentioned in this chapter, the throughput will be improved while focussing on the most important parts with the highest priority. The time that can be saved when we look at the problems from Section 6.2.2 can be (concluding from our time studies) more than 10%, which will obviously have a significant effect on the throughput. This in combination with the focus on producing priority packs will directly result in a higher On Time Delivery for Aerosud in general. The feasibility of the suggestions is also not a problem when it comes to the willingness to change of the employees on the workshop floor. For every suggestion, we first checked with all the employees what their opinion was regarding the suggestions, and for all the suggestions posed above, the employees agreed that they could be very helpful.

7. Step 3 of TOC: Subordinate

In this chapter, we address the third step of TOC, which is the subordination phase. We also give an answer to our fifth research question. The research question that is answered in this chapter is:

What changes can/must be made in the rest of the system to improve the productivity of the CCR if we look at the whole system?

The difference between the second and the third TOC step is that we don't focus on improvement possibilities for the CCR only, but we look at the whole chain in this chapter: we have a non-CCR scope. We answer the research question in two parts. The first part (Section 7.1) is about the solutions that have been found in the previous chapter, and on how these solutions can influence other cells. We look at changes that can or must be made at the other cells that help the CCR-cell. The second part (Section 7.2) is about solution improvements that result from observations that have been done throughout this research. The observations/conclusions that were made in other parts of the research are from the current reality tree and from the time and motion studies.

- Current reality tree: Machine operators "upstream" start batching packs which causes waves of workload in the Assembly cell"
- Time and motion studies: It's hard to determine which batch should be produced next because there are a lot of job stoppers. At some moments, the amount of packs that have a job stopper is almost one third of all the packs present at the Assembly cell.

In this second part (Section 7.2) we also look if and how we can use the tools and methods that have been identified in Chapter 2. The tools that were identified are: Kanban Pull, Visual Management, DBR, 5S, SMED and Kaizen.

- Kanban Pull and DBR come down to the same principle in this chapter: creating flow in the system in which the CCR determines the speed of the process.
- 5S: just as with the previous chapter, the focus is on standardizing within 5S
- SMED is in the scope of the whole chain within this project not really applicable because there are no problems with the changeover times for the products from one work cell to another. Therefore, we won't discuss SMED in this chapter.
- Visual management / Kaizen can also be used when you look at the whole chain.

This means that we have three main things to take into account when generating solutions or suggestions in Section 7.2: DBR (focus on creating flow), Standardizing (5S), and Visual Management (Kaizen). Eventually we will draw a conclusion for this chapter in Section 7.3.

7.1 What should be changed in non-CCR cells based on CCR solutions?

In the previous chapter we came up with 6 possible solutions for the CCR-cell. From these solutions, solution 2, 3, 4 and 6 are solutions that have to be implemented in the cell itself. For that reason, these solutions aren't interesting to discuss in the subordination phase (in which we look at the non-CCR cells). That's also the reason why we don't discuss them any further in this section.

From the solutions posed in Chapter 6, Solutions 1 and 5 are solutions for which help from outside the assembly cell is or can be needed. Solution 1 is the kitting of the complete batches before the batch itself arrives at the cell and it needs to be processed. Solution 5 is that the sequence of the batches that have to be assembled has to be determined using a priority system that is interpreted in the same way by everyone.

Solution 1: pre-kitting the whole PPS

The kitting of all the required things for every batch is important for the flow in the process. The cell leader doesn't have enough time available to kit everything, so it is better to do this "outside" the assembly cell. The best option for this would be if stores kit all the things that are needed. In the current situation, people from stores will bring all the AGSs, parts, consumables, etc. to the assembly cell and store them somewhere in the cell (consumables cabinet/matrix/Floor stock rack/etc.) Then they are sometimes moved within the cell and after that they end up at the work bench with the pack that needs to be assembled. Instead of all these actions, it is also possible to already kit everything at the stores. The people from stores will have to look at all the AGSs and spares that are needed, and kit them together. The expeditor brings these kits to the cell, and the cell leader will divide all the kitted packs with the products and the needed tools/jigs over the work benches. If this is done properly, then the artisans will never have to get their own tools/jigs, AGSs, products, etc. and they can constantly keep producing.

The recommendation that follows from this in short is: Stores should kit all the materials and components that are needed for a batch separately for every batch.

Solution 5: setting a clear priority system

Following a standard policy for priorities is important within the cell itself to only produce the most crucial parts. Outside the cell it's important that one clear rule is communicated which can't be interpreted in several ways. Different people now interpret the rules in slightly different ways, causing undesirable situations in which people make decisions based on TIC, throughput and system priorities. One clear rule should be communicated "from above", so the workshop will produce in the optimal way. Management says that throughput per day isn't important, so that should be communicated to the shop floor as well. As a result of the high variety in processing times, it will become possible to have days on which the throughput is less than 100 parts or days that the throughput is more than 300 parts, but at the end of the year, the throughput will be the same, and the production policy is more based on one of the KPIs: On Time Delivery. A simple way to make the priority system easier is to adjust the system in such a way that at the start of every day the highest (two) TIC value automatically gets a -30 priority or something. In that way, the cell leader can just pick the highest priority as the next pack that should be produced.

The recommendation that follows from this in short is: Management should communicate a clear priority policy that can only be interpreted in one single way. Preferably, an adjustment should be made in the SFDC-system, so the people in the workshop can just follow the sequence that the system shows.

7.2 What should be changed in non-CCR cells based on our model and observations?

In the previous section, we discussed the non-CCR changes that should be made based on CCR solutions that were posed in Section 6.3. In this section, we look at the non-CCR cells in general to see if we can come up with other solutions. But the main focus of this section is using the tools (DBR, Standardizing, and VM) when trying to come up with a solution for the two problems mentioned in the introduction of Chapter 7:

- Current reality tree: Machine operators "upstream" start batching packs which causes waves of workload in the Assembly cell (Section 6.2.1)

  → solution generation for this problem is discussed in Section 7.2.1
- Time and motion studies: It's hard to determine which batch should be produced next because there are a lot of job stoppers. At some moments, the amount of packs that have a job stopper is almost one third of all the packs present at the Assembly cell. (Section 6.2.2)

  → solution generation for this problem is discussed in Section 7.2.2

7.2.1 Upstream batching

One of the conclusions from the current reality tree in Section 6.2.1 about what causes problems for the Assembly cell is that the machine operators "upstream" start batching packs which causes waves of workload in the Assembly cell. For the Assembly cell this is a problem, because it disrupts a normal flow in the whole chain. The reason why people upstream start batching packs together is mainly because of the set-up times at those work cells. When they look into SFDC which pack they should produce next, they will pick the one with the highest priority (which is almost always black). Often, there's also a pack in the system with the same products, but with a lower priority (red, yellow or green). If this is the case at for example the Vac-Form machines, then the operator doesn't want to have to change the tool an extra time a few days later, so he decides to produce all the products in one time. If the operator decides to produce packs that don't have a high priority, and produces them at the same time as high priority packs, then this batching "bubble" with a large quantity of products goes to the next work cell (in this example to NC-Trim). At NC-trim, the operator does the same, which causes the bubble to go through the system until it ends up at Assembly.

These “bubbles” should be prevented. The best way to prevent it is really simple: stop batching packs. However, there are a few things here that need to be taken into consideration. The biggest result of stopping with batching packs in the cells is that the total processing time will go up a bit because of extra set-up times. This won’t be a really big problem, because the work cells upstream aren’t capacity constrained resources. From the Throughput Accounting part in Section 5.1.2, we also concluded that extra work load on the other cells won’t directly increase resource load % to a problematic situation. Therefore, the extra processing time isn’t a problem. Another potential problem is that it doesn’t make practical sense to produce for example product A, then B, and then A again. Therefore it is a good idea to make a batching policy (e.g. only batch parts with a priority that’s black or red).

The recommendation that follows from this in short is: The operators that work at non-CCR cells have to stop batching products because of ease of work. Since this sometimes won’t make any practical sense, we suggest to make a batching policy to find the best way to work with, with the best results.

7.2.2 Job stoppers

One of the main observations in Chapter 6 was that there are a lot of job stoppers in the assembly cell. This is bad for the cell and the products, since the cell has products in it which can’t be worked on and the products take a longer time to be finished. It is important that the job stoppers are investigated thoroughly and that the root causes are found. Only then conclusions can be drawn on what action should be taken. For example: if product A needs subassembly B and subassembly C and product A has a job stopper, then we have to look what the job stopper is: subassembly B or C? If we determined that, then we should look at the reason why this certain subassembly part is a job stopper, and so on, until we find a root cause. If we find the same root cause often, then that is an indication that something should be changed in for example the buffer of certain products.

One of the things that we already observed is that for example product A is released into the system, because subassembly B and C are both in stores. But as soon as those sub assembly parts are needed for product A, all the subassembly parts can already be used for different products, causing a job stopper for product A. A solution for this would be: only release products into the system when their sub assembly parts are all finished, and already link these subassembly parts to a certain PPS so that it can’t cause a job stopper in the Assembly cell.

The recommendation that follows from this in short is: try to find the root cause of the job stoppers, and evaluate for example the standard buffer if a root cause occurs often. Also link all the sub assembly parts in the system to a certain PPS already, so that when releasing a product, you can be sure that all the sub assembly parts will be ready when they’re needed and won’t cause a job stopper anymore.

7.2.3 Chain analysis: chain broad problems and solution generation using tools from our model

In Chapter 2, we identified a few tools that can be used during this step. In the introduction of this chapter, we identified the following tools to work with in this chapter: DBR (focus on creating flow), Standardizing (5S), and Visual Management (Kaizen).

- DBR (focus on the Buffer and the Rope: "creating flow")

There is a simple way to create more flow in the system. When talking to employees at Aerosud, we found out that currently, PPSs are launched in the system on basis of their delivery date. Sometimes, when busy periods are ahead, it makes sense to start producing packs earlier. The only problem is that people can start batching then more easily, which will cause problems again. Therefore our suggestion would be to set a standard number of packs that will be released into the system every day. This standard amount that is released should be based on the average daily demand, and in that way more flow will be created in the system.

- Standardizing (5S)

The solution mentioned above is also one way of standardizing. There are not really any other problems in the system that haven't been addressed yet for which standardizing could be valuable.

- Visual management

The system broad solution that results from VM is more a result of the solution in Chapter 6 where we concluded that the operators and artisans can't really see how they're performing really good. This is the case throughout the whole production chain, and therefore we would suggest to visualize every work cell's performance within the workshop, so that everybody is constantly triggered to do the best they can.

7.3 Chapter summary and conclusion.

In this chapter we found a few solutions. The solutions that we've found for the problems that are system wide are:

- The operators that work at non-CCR cells have to stop batching products, because of ease of work. Since this sometimes won't make any practical sense, we suggest to make a batching policy to find the best way to work with, with the best results.
- Try to find the root cause of the job stoppers, and evaluate for example the standard buffer if a root cause occurs often. Also link all the sub assembly parts in the system to a certain PPS already, so that when releasing a product, you can be sure that all the sub assembly parts will be ready when they're needed and won't cause a job stopper anymore.
- Set a standard number of packs that will be released into the system every day.
- Visualize every work cell's performance within the workshop, so that everybody is constantly triggered to do the best they can.

The first and third solution will mostly increase the flow in the system, which will direcly improve the flow out of the system and in that way the On Time Delivery. The second solution will directly improve the On Time Delivery, because high priority products are produced earlier. For the last solution it's hard to say what the effects will be. The absolute effects on how much all the solutions can improve the On Time Delivery is not possible to estimate, because you can't calculate the real results of those actions.

8. Conclusions and recommendations

In this chapter, we will first briefly discuss the conclusions from this research project. We discuss all the conclusions in Section 8.1. After that, in Section 8.2 we try to translate some of our solutions into concrete recommendations which Aerosud can use directly.

8.1 Conclusions

Throughout this research project, we first identified how the whole system works in Chapter 4. After that, we carried out the first three steps of TOC.

We started with the constraint identification, which is the first step of TOC, in Chapter 5. In this Chapter we identified some potential constraints. We evaluated all the potential constraints on the reliability of the data that was used to find that potential constraint in combination with the expected impact that it could have on the system. We eventually identified the Vac-Form Assembly cell as the system's constraint.

The second step of TOC, the constraint exploitation, was carried out in Chapter 6. In this chapter we zoomed in on the Assembly cell and we did several things to analyse the cell: a detailed cell description and a cell analysis. In the cell analysis, we used the current reality tree, time and motion studies, and we used the tools that were identified in the literature. Eventually we came up with a few solutions that will help the CCR:

- Pre-kitting the entire packs
- distributing packs to/from the work benches by the cell leader
- Buying extra accessory should be bought (jigs, tools, etc.)
- Identifying production times per product family so they can be measured
- Artisans shouldn't be able to decide which pack is next: this is the cell leader's job
- Clear indication on the cell performance (for the artisans) should be visible at all times

After that, we started with the third step of TOC: the subordination phase. In that phase, we subordinated our suggestions for the CCR-cell to the rest of the system. The focus in the third step of TOC is to look at system broad solutions and improvements for the whole chain. The solutions that resulted from the subordination phase are:

- No batching at non-CCR cells (or only according to a strict batching policy)
- Thoroughly investigate the cause of job stoppers. Also link all the sub assembly parts in the system to a certain PPS already, so that when releasing a product, you can be sure that all the sub assembly parts will be ready when they're needed and won't cause a job stopper anymore.
- Pre-kitting the entire packs at stores

- Setting a clear priority system that is interpreted the same by everyone.
- Releasing a standard number of products per day to create flow in the system
- Visualizing every work cell's performance within the workshop

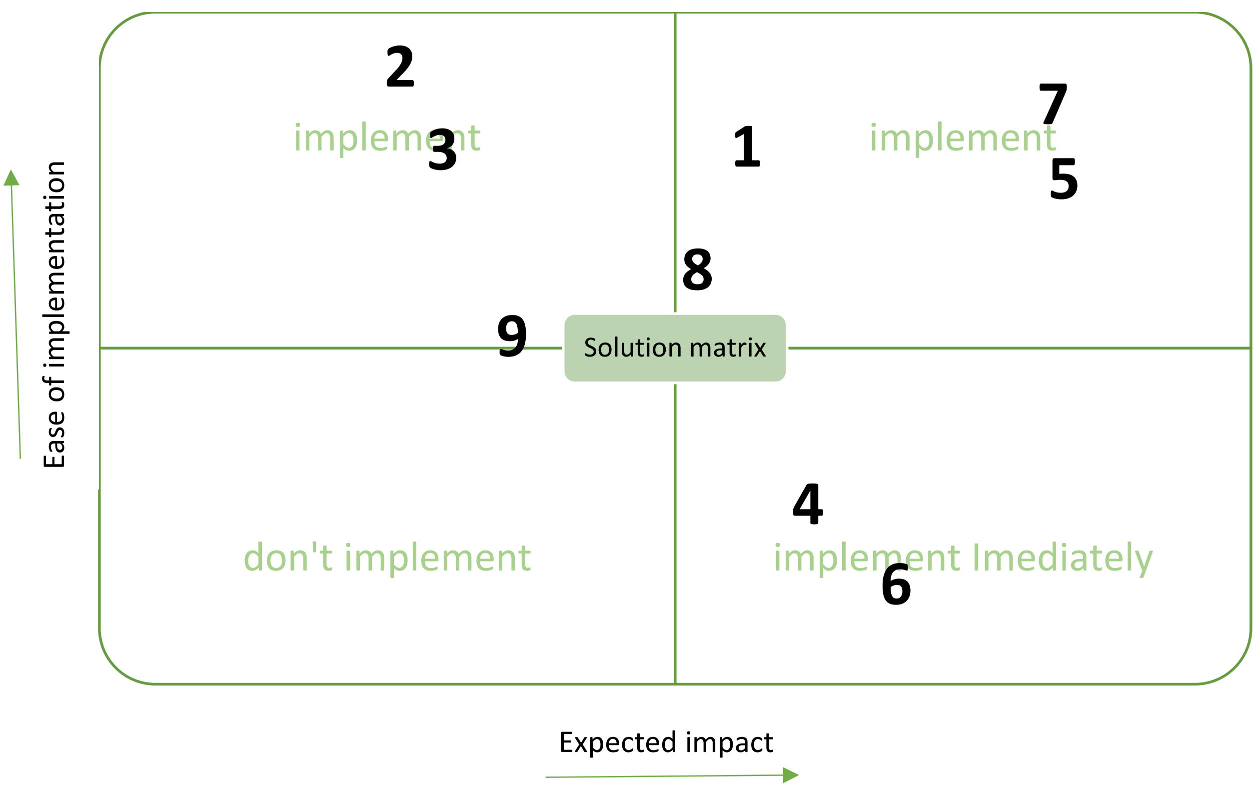
8.2 Recommendations

In 8.1 we discussed the different solutions/suggestions that resulted from this research project. In this section we try to find concrete recommendations on what Aerosud can do now. The recommendations that we mention below are a result of conversations with the management and cell leaders at Aerosud in which we decided which suggestions can or should be implemented and which solutions shouldn't. The recommendations for Aerosud are:

1. Try for 1-2 months how batching at stores would help the assembly cell and after that determine if the solution should be implemented or not.
2. The cell leader should place the next batch for every artisan at their work bench already so they don't have to look for the next batch and no time is wasted. If the cell leader does this all the time, then he'll have a better overview of everything, and a lot of time will be saved.
3. Buy the extra accessory mentioned in Chapter 5
4. Make an action plan on how production times can be identified more specific than now so that performance can be measured more easily and evaluate if it can be implemented.
5. Stop batching at non-CCR cells (or only according to a strict batching policy)
6. Thoroughly investigate the cause of job stoppers. Also link all the sub assembly parts in the system to a certain PPS already, so that when releasing a product, you can be sure that all the sub assembly parts will be ready when they're needed and won't cause a job stopper anymore.
7. Setting a clear priority system that is interpreted the same by everyone and that is based on KPIs that are based on the company's KPIs. TIC is not a result from Quality or On Time Delivery, so first of all the KPIs should be re-evaluated.
8. Release a standard number of products per day to create flow in the system
9. Visualize every work cell's performance within the workshop

These are the recommendations that result from all the suggestions that have been made throughout this research. To come to these 9 solutions, we evaluated all the suggestions together with Aerosud and ended up with these 9. To make it easier to keep an overview, and to make the implementation more manageable, we put all the final recommendations in a solution matrix where you can see the expected impact of the action and the ease of implementation of the action. To put the solutions in this matrix, we didn't have absolute values, but tried to put them in the matrix relative to eachother. From this solution matrix, in combination with the available time at Aerosud for certain actions, Aerosud can choose when to implement which solution.

Our suggestion is to start with the easy changes that have a high impact (4 and 6) and then start with the suggestions that appear first if you follow the matrix counter clockwise: 5 – 7 – 8 – 1 – 2 – 3 – 9.



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Appendix A: Literature review justification

The literature question that we aim to answer using the literature research is: “Which tools and methods are used for a successful TOC implementation and can be used to combine with Dettmer’s model? ”

Inclusion and exclusions criteria

For the systematic literature review we set up a few inclusion and exclusion criteria. Underneath, you can find two tables of criteria that have been used for the inclusion or exclusion of certain pieces of literature. These criteria have been used to make a selection of the different literature pieces after deletion on basis of the number of citations.

INCLUSION	CRITERIA	REASON
1	Focus on improving	Improving is more relevant for this study than controlling.
2	Providing an overview on tools/methods of TOC	Because we don’t know a lot about TOC tools and methods yet, it is very interesting to find out more about it. If an article provides a clear overview, then that would be very helpful
3	Combination lean/toc	Most interesting to find different views on how both compare to each other, which can be used easily for the final conclusion. A lot of literature pieces shortly mention the existence of one of the to, but don’t really combine it, which makes them less interesting. This isn’t directly the scope for the literature question, but will be very interesting in addition to the other information.

EXCLUSION	CRITERIA	REASON
1	Service companies	In this research the focus is on production. There is literature enough, so for that reason service companies are not interesting enough.
2	Six sigma	Six sigma is very often part of literature pieces about lean or TOC. This can sometimes be confusing. Therefore, pieces with a frequent use of this term will be excluded.
3	Older than 1990	Before then, lean wasn’t really well known, and TOC only existed since 1984.
4	No proper referencing	When I want to go deeper into something but can’t find were certain statements come from, than certain statements can be unclear.

5	Focus on controlling	For this research I don't want to control a situation but want to improve something.

Search Strings

After the inclusions and exclusion criteria have been determined, we set up the search strings. Because Dettmer's model is already known and we have more knowledge about lean that about TOC, we mainly focus on TOC in this literature research. As you can see, three of the four search strings only focus on TOC. The information that we find by doing this research can be combined with Dettmer's model and the lean tools that we already know about. One of the four search strings

The database that is used is "Scopus" because other databases don't give specific enough results, or they have problems with availability often.

Search term A		**Search term B**		**Other terms**	**Number of results**
Theory of Constraints	AND	Implementation	AND OR OR	Tools Methods Techniques	84
Theory of Constraints	AND	Barriers	OR OR	Strengths Weaknesses	19
Theory of Constraints	AND	Identify	OR OR	Exploit Subordinate	135
Theory of Constraints	AND	Lean	AND OR OR	Combine Combining Combination	16
				Total number of results	254
				After deleting duplicates	198
				After deleting on basis of inclusion/exclusion criteria	123
				After reading title	41
				After reading abstract	13
				Based on availability	9
				After reading	7
				After backward search	16

Appendix B: CCR identification using Throughput Accounting

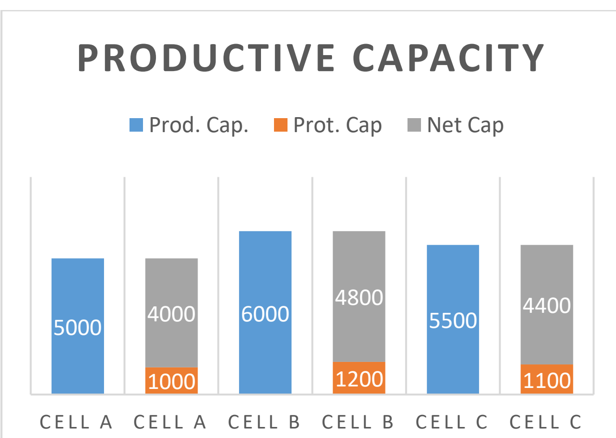
General

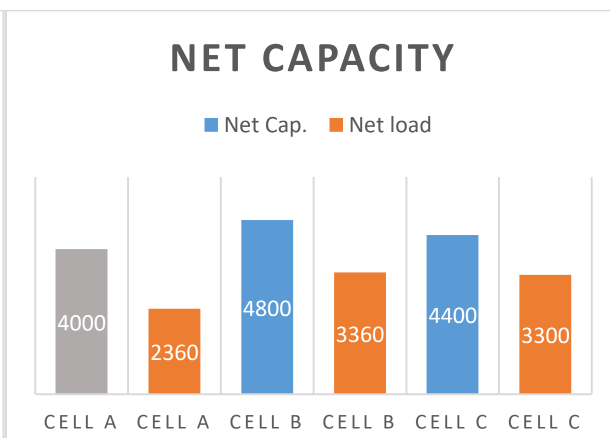
Productive capacity = Available time on every machine (365 days *24 hours, minus the company policies and machine setups, breakdowns, maintenance) → All the cells in the Vac-form line have slightly different number of hours available due to difference values for the setups, breakdowns and maintenance. The company policy is the same for all the cells (weekends, public holidays and standard closing hours). The machine set up, breakdowns or maintenance only has a relatively small impact on the values. The main value that influences the machine's productive capacity are the policies (which are the same everywhere) so the productive capacity is more or less the same for every work cell.

Net capacity = the capacity that's available after subtracting the protective capacity (a certain percentage) from the productive capacity. The standard protective capacity that is used at Aerosud for simple calculations/examples like this is 10%. For that reason, we also use 10 % protective capacity in our research.

The net load capacity is the number of hours that is needed to complete the demand on for that cell. This value is calculated by dividing all the products into product groups, determine the demand of every product group in products, and multiply that by the production time for one product of that product group/family. After that, all the production time from every product group can be added together, and the total load is determined.

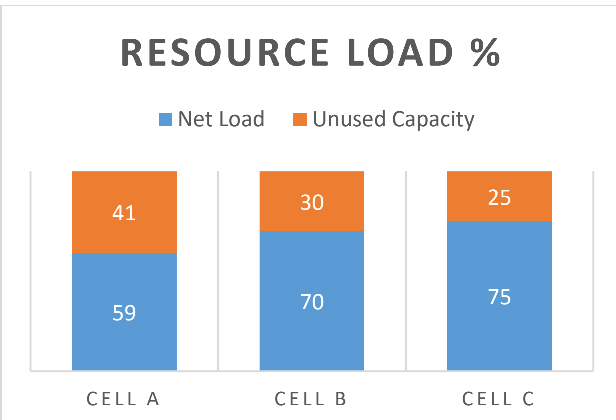
For example:





(in this example we use a protective capacity of 20%, to make the example more obvious)

In this example we see that the productive capacity is all more or less the same. From that productive capacity, we subtract 20%, to come to our Net Capacity. After we determined the Net Capacity, we must determine the Net Load. In this example, you can see that Net Load can have a quite big relative difference, which is also the case in real life. Now that we have determined a Net Capacity and a Net Load, we can simply look at the proportion of the Net Load when you compare it to the Net Capacity. This is done in the diagram below. The CCR is the cell that is the closest to its own net capacity (in %). We call this the resource load percentage. In this example, Cell C has the highest relative Resource Load, so also the highest Resource Load percentage. So, in this example, Cell C is the potential CCR when trying to determine the CCR using simplified Throughput Accounting.



→ **Potential CCR = Cell C**

Data that is needed to determine the CCR:

Productive Cap:

Data needed for every cell:

a. policies,
b. setup times,
c. breakdown times,
d. maintenance hours,
→ productive capacity for every cell in days per year = (365 – a – b – c – d)
→ productive capacity for every cell in hours is that value multiplied by 24

Net Cap:

- Percentage for protective capacity (in report 10%, in this example 20%)
→ net capacity for every cell per year = (100%-protective cap.) x productive capacity

Net load:

a. Different product groups for every workcell
b. The time that is needed per product of every product group
c. The demand in number of products of every productgroup per year
→ Net load = Sum of BxC over all the product groups A

Resource Load percentage = Net load / Net Cap

➔ Highest Resource load percentage = CCR

Appendix C: Hofstede's cultural dimensions

Power Distance Index (PDI)

This dimension expresses the degree to which the less powerful members of a society accept and expect that power is distributed unequally. The fundamental issue here is how a society handles inequalities among people. People in societies exhibiting a large degree of Power Distance accept a hierarchical order in which everybody has a place and which needs no further justification. In societies with low Power Distance, people strive to equalise the distribution of power and demand justification for inequalities of power.

Individualism versus Collectivism (IDV)

The high side of this dimension, called individualism, can be defined as a preference for a loosely-knit social framework in which individuals are expected to take care of only themselves and their immediate families. Its opposite, collectivism, represents a preference for a tightly-knit framework in society in which individuals can expect their relatives or members of a particular in-group to look after them in exchange for unquestioning loyalty. A society's position on this dimension is reflected in whether people's self-image is defined in terms of "I" or "we."

Masculinity versus Femininity (MAS)

The Masculinity side of this dimension represents a preference in society for achievement, heroism, assertiveness and material rewards for success. Society at large is more competitive. Its opposite, femininity, stands for a preference for cooperation, modesty, caring for the weak and quality of life. Society at large is more consensus-oriented. In the business context Masculinity versus Femininity is sometimes also related to as "tough versus tender" cultures.

Uncertainty Avoidance Index (UAI)

The Uncertainty Avoidance dimension expresses the degree to which the members of a society feel uncomfortable with uncertainty and ambiguity. The fundamental issue here is how a society deals with the fact that the future can never be known: should we try to control the future or just let it happen? Countries exhibiting strong UAI maintain rigid codes of belief and behaviour and are intolerant of unorthodox behaviour and ideas. Weak UAI societies maintain a more relaxed attitude in which practice counts more than principles.

Long Term Orientation versus Short Term Normative Orientation (LTO)*

Every society has to maintain some links with its own past while dealing with the challenges of the present and the future. Societies prioritize these two existential goals differently.

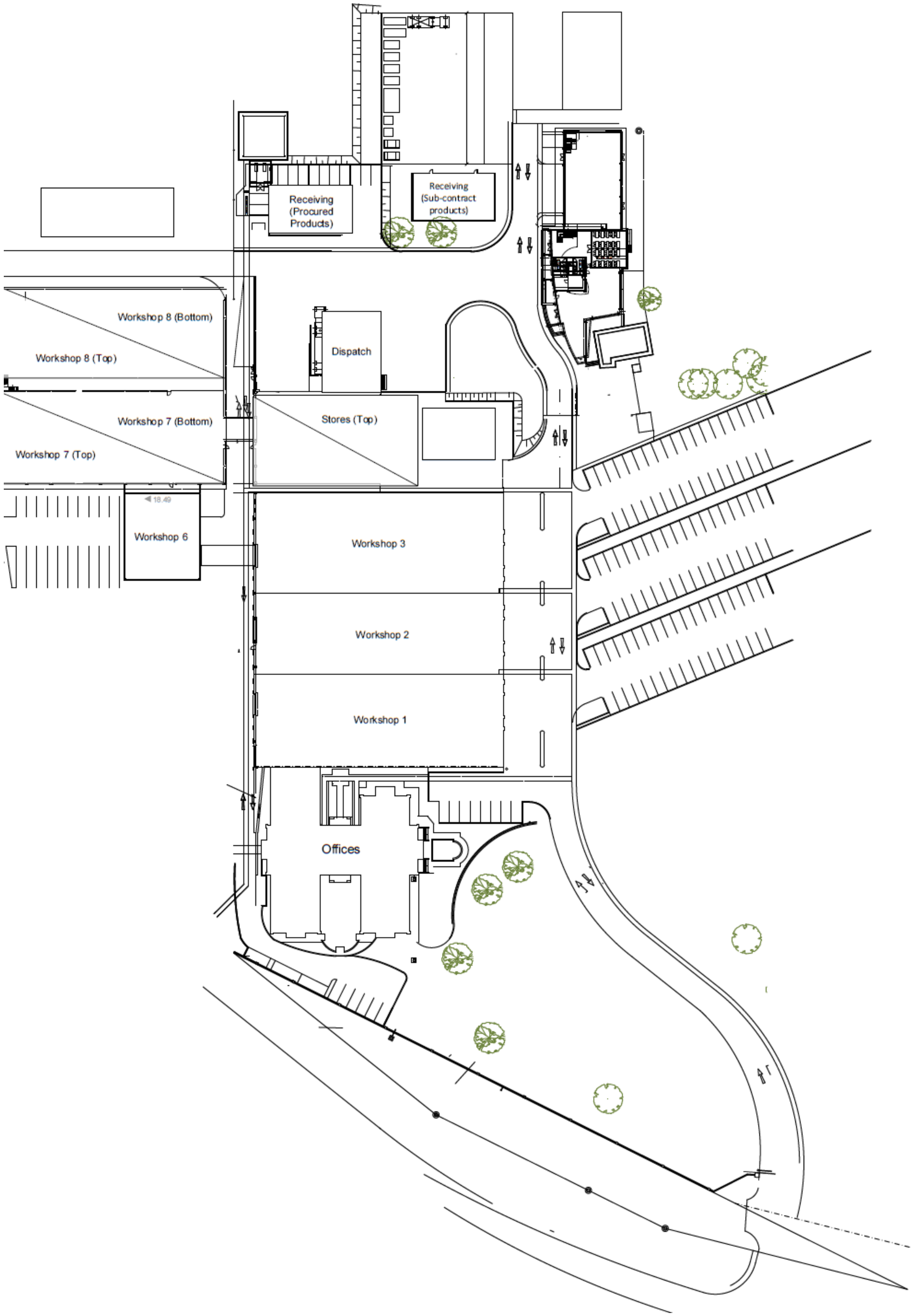
Societies who score low on this dimension, for example, prefer to maintain time-honoured traditions and norms while viewing societal change with suspicion. Those with a culture which scores high, on the other hand, take a more pragmatic approach: they encourage thrift and efforts in modern education as a way to prepare for the future.

In the business context this dimension is related to as "(short term) normative versus (long term) pragmatic" (PRA). In the academic environment the terminology Monumentalism versus Flexhumility is sometimes also used.

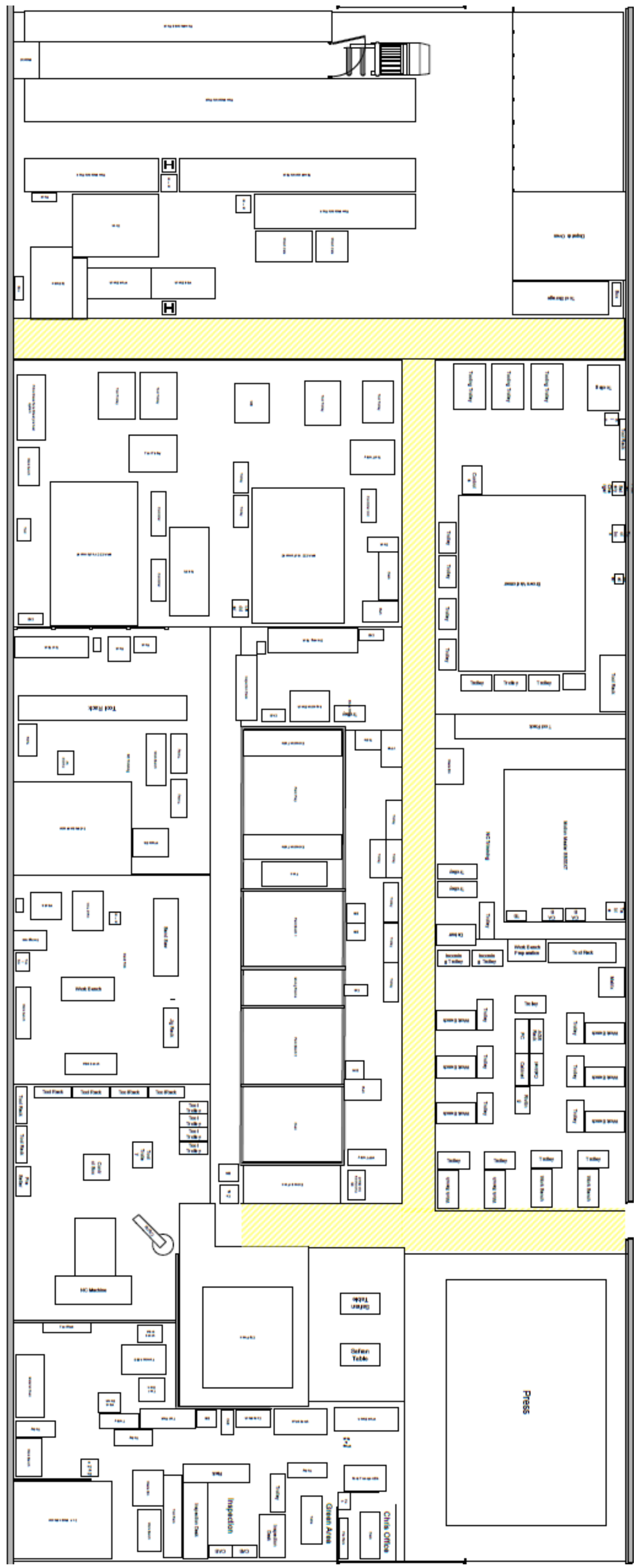
Indulgence versus Restraint (IND)

Indulgence stands for a society that allows relatively free gratification of basic and natural human drives related to enjoying life and having fun. Restraint stands for a society that suppresses gratification of needs and regulates it by means of strict social norms.

Appendix D: Aerosud layout



Appendix E: Workshop 1 layout



Appendix F: Data used for Throughput Accounting

See excel documents:

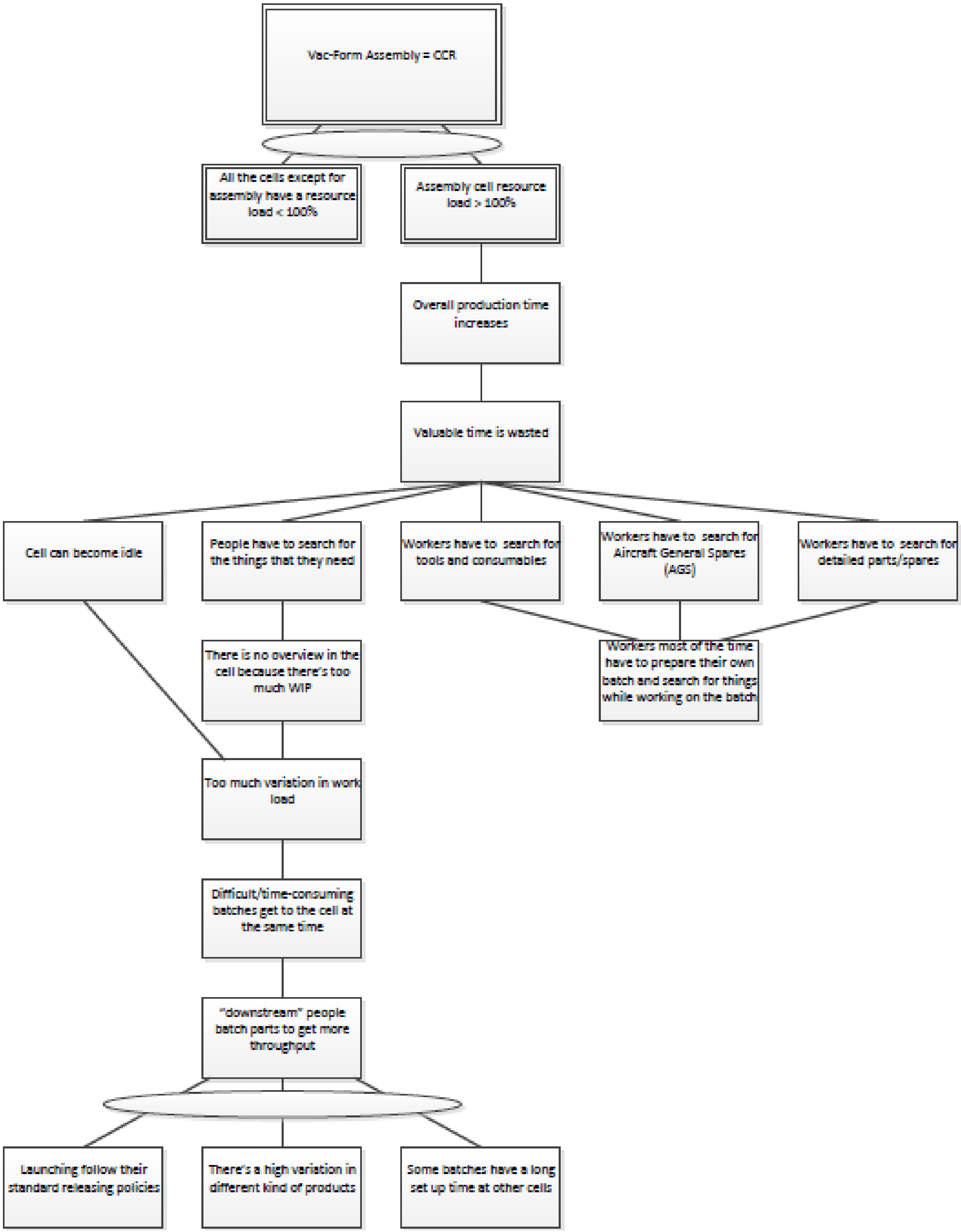
“ Main Database - asset Register - info for productive capacity “

“ Net Resource Load - info for net load “

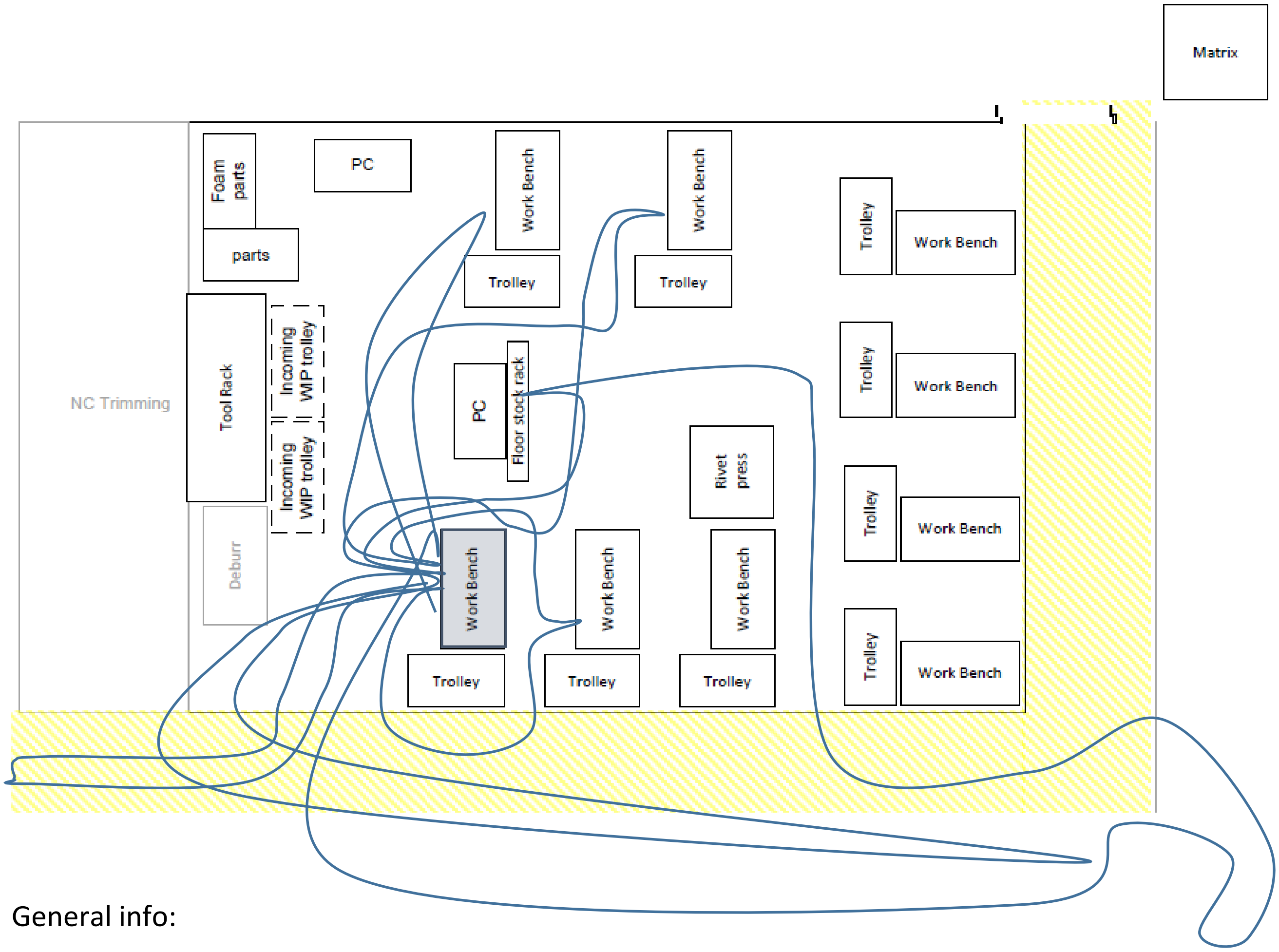
“ Productive capacity per work cell “

“ resource load calculations per work cell “

Appendix G: Current reality tree



Appendix H: Time and Motion studies Assembly cell

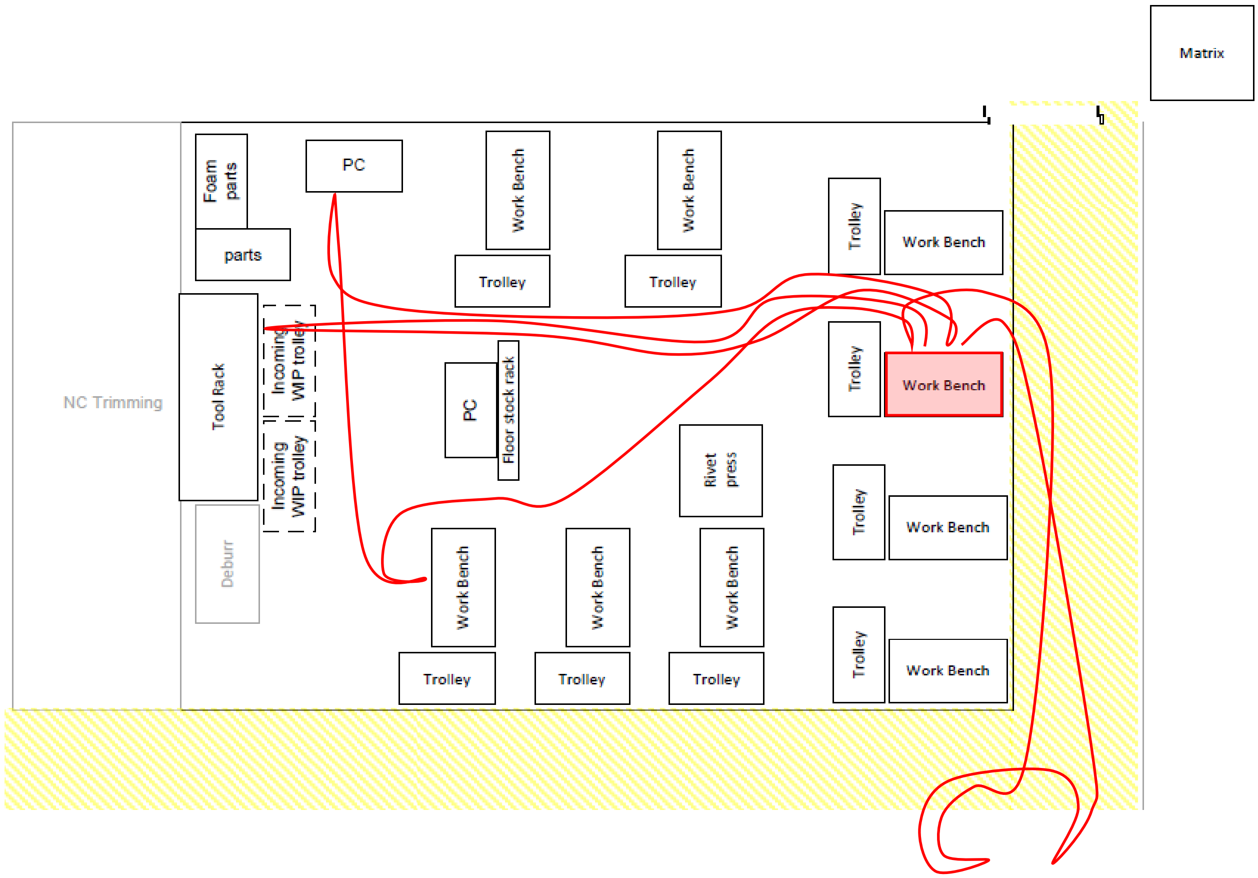


General info:

- Total time measured: 30 minutes
- Total time wasted on getting tools and other things: 4 minutes (13% of the total time)
- Half a batch completed.

Activities of the operator:

- borrow tools from other work benches
- get scotch brite (sort of sanding paper) from a different work cell (paint prep)
- search the floor stock rack for rivets that he needed for his batch
- search for tape at other work benches (because it wasn't available in the consumables stock.
- talking

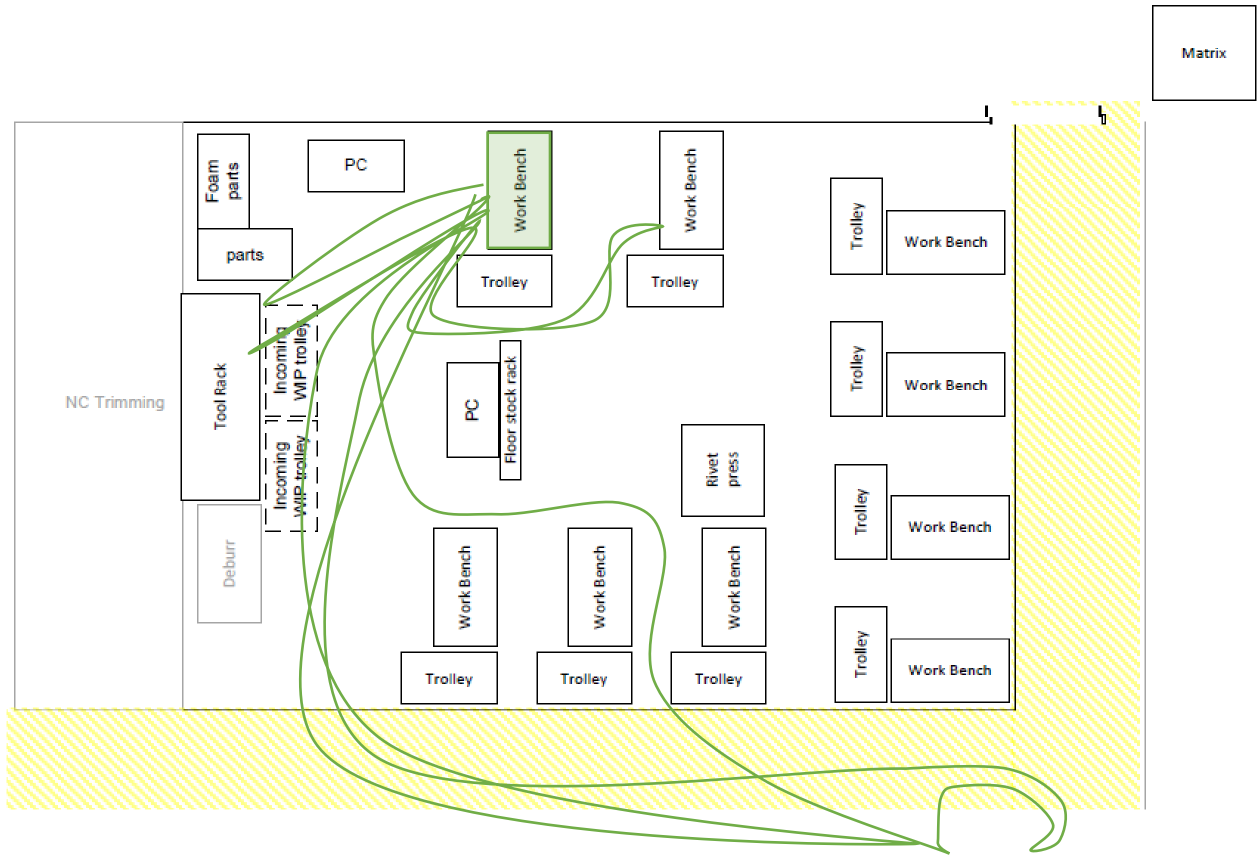


General info:

- Total time measured: 25 minutes
- Total time wasted on getting tools and other things: 3 minutes (12% of the total time)
- 0.25 batch completed.

Activities of the operator:

- borrow tools from other work benches
- check the pc
- get consumables that have run out
- talking

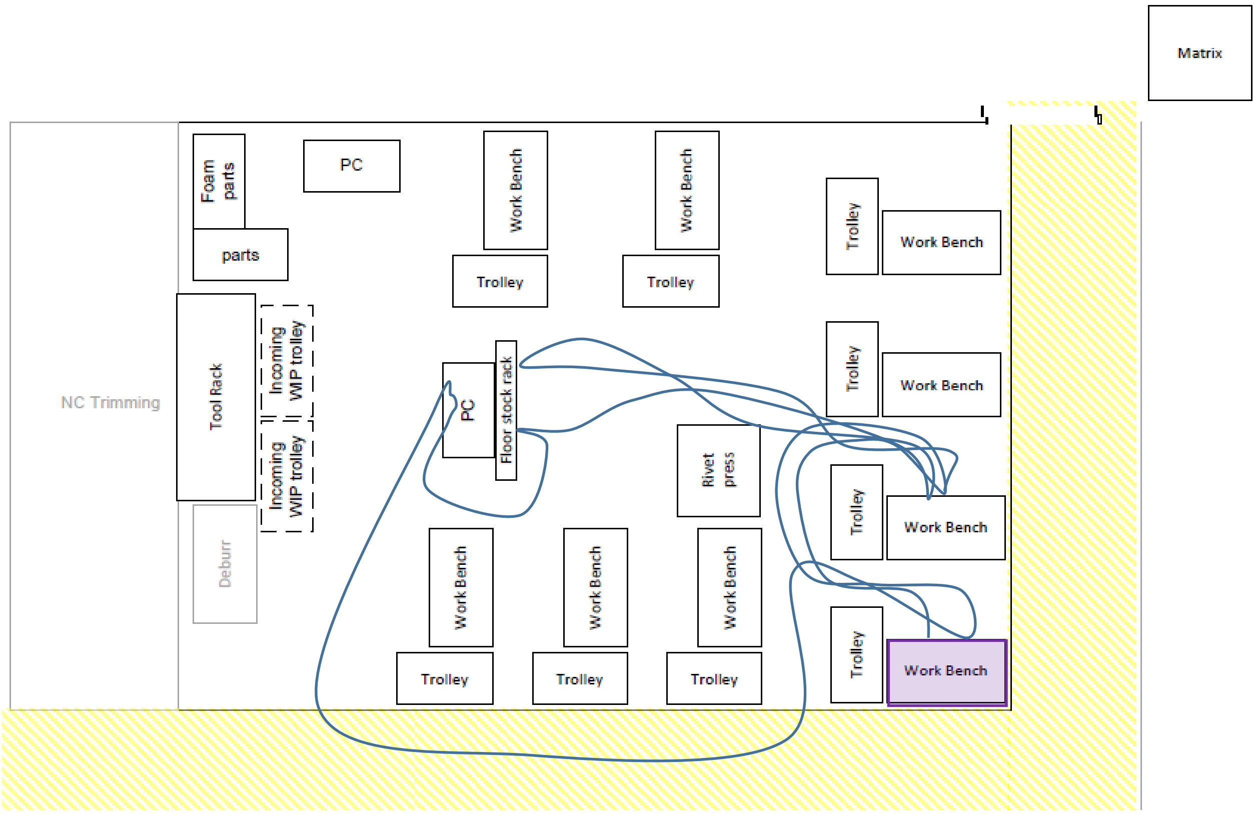


General info:

- Total time measured: 22 minutes
- Total time wasted on getting tools and other things: 4 minutes (18% of the total time)
- 0.25 batch completed.

Activities of the operator:

- Get valcro from the consumables cabinet and bring it back
- Cut valcro in the right sizes
- search for the shop aids
- talking



General info:

- Total time measured: 18 minutes
- Total time wasted on getting tools and other things: 3 minutes (17% of the total time)
- 0.25 batch completed.

Activities of the operator:

- Get drill from other table
- Get AGSs
- talking