A BOTTLENECK ANALYSIS TO INCREASE THROUGHPUT AT APOLLO VREDESTEIN B.V.

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Management summary

We perform this research at Apollo Vredestein B.V as a Master thesis for the study Industrial Engineering & Management and specialization Production and Logistics Management. The tyres of Apollo Vredestein have become more diverse and this has increased the complexity within the production site. Not all processes are adapted to this change, which has increased the production costs per tyre. To be able to compete, it is crucial for Apollo Vredestein to improve their efficiency and with that lower the costs per tyre. To achieve both lower costs per tyre and a higher throughput, we decide to improve performance by following the concept called Theory of Constraints. Therefore, we define the main research question as follows:

"How can Apollo Vredestein identify the most significant bottleneck machine within the production line of agricultural and space master tyres, improve the most significant bottleneck machine, and align non-bottleneck machines to increase the throughput of the system?"

Bottleneck identification

We limit this research to the production line of agricultural and space master tyres. To set up the bottleneck identification process, we take the requirements of Apollo Vredestein and the characteristics of the bottleneck identification methods known in literature into account. We set up a bottleneck identification process that consists of four phases. The first phase filters on data availability to identify non-bottlenecks. The second phase performs the turning point method and the third phase performs the utilization method to identify the bottleneck. Finally, the fourth phase gives a conclusion on the location of the bottleneck and validates the result. After executing the bottleneck identification process, we conclude that the current bottleneck is a machine called the ART. The ART is a bead-making machine that produces beads for both agricultural and space master tyres.

Bottleneck improvement

We perform a root cause analysis to define a focus of improvement at the bottleneck machine. We formulate the problem as "limited throughput at the ART". We use an Ishikawa diagram to present an overview of the potential causes and we arrange them in a Probability-Impact Matrix. Using this matrix, we decide that improving the cause "fine-tuning of the machine" is of the highest importance. To decrease the amount of time that is spent on fine-tuning of the machine, Apollo Vredestein should limit the possibilities to fine-tune. First, by creating an agreed upon setting or settings. Second, by making some settings that do not have to be accessible non-accessible for operators. Because this solution requires a very thorough understanding of the machine and the effects of certain components, we recommend the process technologist to improve this cause. Furthermore, we conclude from the Probability-Impact matrix to focus on a second cause. We focus on the cause "no wrapping material" and specifically on the two sub-causes "the length of a roll is not measured and not booked" and "the current buffer for wrapping material is not sufficient". Improving these sub-causes contributes to subordinating or aligning the non-bottleneck processes.

Subordinate non-bottleneck processes

Apollo Vredestein can reduce the shortage of wrapping material by improving the accuracy of the inventory of wrapping material and by implementing an inventory control policy to buffer against uncertainties. We set up a measurement method to estimate the length of a roll from the diameter of a roll and use this method to generate data on the length of a roll of wrapping material. We

analyze the data and decide whether we should change the current approach of booking 250 meters per roll. There are two options to improve the accuracy of the inventory. The first option is adjusting the amount of meters booked per roll of wrapping material from 250 to 216 meters. This solution improves the accuracy with the least effort but does not offer a precise representation of the inventory. This option can be expanded by manually measuring small rolls that are outliers. After the operator measures the diameter, he or she can manually enter the diameter in PIBS (the production information and control system used within Vredestein) and PIBS estimates the corresponding length. This option requires a little bit of time from the operators, because measuring the diameter is only required for a very small amount of rolls. The second option is to measure the length of a roll in each batch. This can be done by manually measuring the diameter of the roll, entering the diameter in PIBS and with that estimating the corresponding length. Because one roll of each batch needs to be measured, this option requires more time from the operator. It can also be done by adding measuring equipment at the machine where wrapping material is produced, the ORION. Then, it does not require time from the operator, but it does require an initial investment for the measuring equipment.

We also compare some inventory control policies and set up an inventory control policy for Apollo Vredestein to reduce the shortage of wrapping material. We decide a (R,s,Q) policy goes best with the situation at Apollo Vredestein, because it has a periodic review period, a fixed order quantity and the possibility to order a multiple of Q. Using this policy, every R units of time the inventory position is reviewed. If the inventory position is at or below the reorder point s, an integral multiple of a fixed quantity Q is used, such that the inventory position is raised to a value between s and s + Q. If the inventory position is above s, no order is placed until the next review moment. Internal supply uncertainty caused by queue waiting time and internal demand uncertainty caused by scrap are the two major types of uncertainty taken into account for determining the parameters. There are two stock keeping units (SKUs) of wrapping material: HE01-00-0034 and HE01-00-0038. For SKU HE01-00-0034 the policy has a review period R of one shift, order quantity Q of 40 rolls and safety stock SS of 1 roll. For SKU HE01-00-0038 the policy has a review period R of one shift, order quantity Q of 81 rolls and safety stock SS of 2 rolls. Given that the amount of meters booked per roll of wrapping material is updated to 216 meters, these parameters result in a weighted average fill rate P_2 of 0.9997. This equals a yearly shortage of 597.7 meters or 82 minutes.

Recommendations

We recommend reducing the amount of shortage of wrapping material by implementing the option to adjust the amount of meters booked per roll of wrapping material from 250 to 216 meters. We recommend expanding this option with manually measuring and booking small rolls that are outliers. If the shortage of wrapping material has improved sufficiently (by assessment of Apollo Vredestein), we recommend maintaining this solution. If it has not improved sufficiently, we recommend to start measuring and booking the length of each roll. Depending on the preference of Apollo Vredestein this can be done by manually measuring or automatically measuring with (to be installed) measuring equipment. We recommend to further reduce the amount of shortage of wrapping material by implementing the (R,s,Q) policy. Also, we recommend Apollo Vredestein to continue to identify the bottleneck in the future. This can be once a month or once every few months. If the ART remains the bottleneck after implementing the recommendations described so far, we recommend decreasing the amount of time that is spent on fine-tuning the machine and, if necessary, some other causes identified in the root cause analysis.

Abbreviations

AGRI	AGRIcultural
BPR	Business Process Re-engineering
C	Storage capacity
IE	Industrial Engineering
KPI	Key Performance Indicator
LM	Lean Management
MHE	Material Handling Equipment
NGT	No GreenTyre
PCT	Passenger Car Tyres
PIBS	Productie Informatie en BesturingsSysteem. Translates to: Production Information and Control System
PIPO	Periodieke Inspectie Preventief Onderhoud. Translates to: Periodic Inspection Preventive Maintenance
Q	Order quantity
R	Review interval/period
RM	Replacement Market
S	Order-up-to level
s	Reorder point
SiS	Six Sigma
SKU	Stock Keeping Unit
SM	Space Master
SS	Safety Stock
TB	Blockage times
TBM	Tyre Building Machine
TOC	Theory Of Constraints
TQM	Total Quality Management
TS	Starvation times
WIP	Work In Process

Content

1. Introduction

This chapter describes the research approach. First, in Section 1.1 we introduce the company where the research takes place. Section 1.2 gives the motivation for the research. Next, Section 1.3 elaborates on the definition of the bottleneck. Section 1.4 introduces the management concept called Theory of Constrains. We formulate the research objective in Section 1.5. Section 1.6 gives information about the organizational structure and Section 1.7 contains a root cause analysis. Section 1.8 gives the scope of the research. Finally, Section 1.9 presents the research questions.

1.1 About Apollo Vredestein

Vredestein is established in the Netherlands in 1909 and has a rich heritage in the world of car tyres. With a legacy of over 100 years, the Vredestein brand has achieved premium brand status in the automotive industry. Today, Apollo Vredestein B.V. is part of Apollo Tyres Ltd from India. Apollo Tyres is a multinational with offices all around the world. Figure 1.1 shows a map with all the Apollo offices and plants around the world. Apollo Vredestein manufactures and sells high quality tyres and their tyres have won multiple awards. They sell for both brands Apollo and Vredestein in Europe. Beyond Europe the tyres are available in over 100 countries across the globe. The head office of Apollo Vredestein is in Amsterdam and the manufacturing sites are in Enschede and Gyöngyöshalász (Hungary).

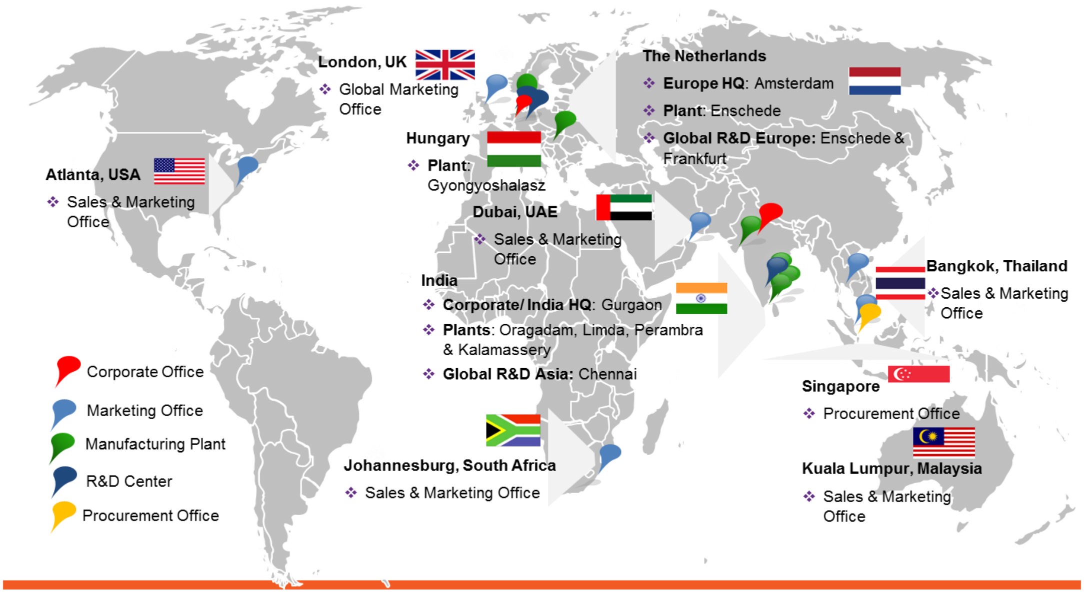


Figure 1.1: *World map with all Apollo offices and plants. Reprinted from "corporate-presentation2017", by Apollo Vredestein B.V., 2017.*

The company delivers two types of markets, *Original Equipment* Manufacturers and *Replacement Market*. Original Equipment (OE) tyres are supplied directly to the vehicle manufacturers that assemble vehicles in their assembly plant. Thus, these tyres are used in new cars that are yet to be sold. The Replacement Market (RM), also called aftermarket, supplies accessories, spare parts, second-hand equipment, and other goods and services used in repair and maintenance. Apollo Vredestein supplies tyres to the RM that can be used for instance if a tyre is worn out. Within these two markets they deliver to three sectors: Passenger Car Tyres (PCT), Space Master Tyres (SM) and

Agricultural Tyres (AGRI). Figure 1.2, Figure 1.3, and Figure 1.4 respectively represent the three tyre sectors.

Figure 1.2: *PCT tyres.*

Figure 1.3: *SM tyres.*

Figure 1.4: *AGRI tyres.*

Their tyres are very diverse, also within the tyre sector. There are many different sizes, profiles and specifications that lead to a large amount of stock keeping units (SKUs). Most are obvious differences such as the size, profiles, or purpose (for instance summer/winter). Figure 1.5 shows an example. The tyres on the left and right are both AGRI tyres, but they have a different size and profile and thus look very different. However, sometimes the tyre diversity is not even visible for the eye. Figure 1.6 and Figure 1.7 present an example: the tyres have the exact same size and profile, but a different load index. The load index refers to the maximum weight that a tire can support when properly inflated. A higher load index means that the tyre can support a higher weight. The tyres have different layers of ply, layers of breaker and a different strength of the bead to achieve a specific load index. Thus, these are two tyres with different specifications and a different construction, but they have the same appearance. This is an example for AGRI tyres, but the same sort of examples can be found for PCT and SM tyres.

Figure 1.5: *Visible tyre differences.*

Figure 1.6: *AGRI tyre 540/65R30 (143 D).*

Figure 1.7: *AGRI tyre 540/65R30 (150 D).*

1.2 Research motivation

The tyres of Apollo Vredestein have become more diverse and this has increased the complexity within the production site. Not all processes are adapted to this change, which has increased the production costs per tyre. To be able to compete, it is crucial for Apollo Vredestein to improve their efficiency and with that lower the costs per tyre. Also, in the current situation the production planning does not take the bottleneck into account, creating erratic flow and congestion. This results in an average of 7.3% starvation at the curing department of PCT, SM and AGRI over the past year, see Figure 1.8. Starvation is the time that a machine is idle, because it is waiting for parts from upstream. This means that on average 7.3% of the time that the machine is available, it cannot produce because it has no input materials. Apollo Vredestein plans on the curing department, which means that all starvation losses at the curing department result in lost tyres that could have been sold. The available time of all curing machines in an ordinary week equals 1,632,960 minutes. Thus, 7.3% is equal to 119,206 minutes and one machine has 10,080 available minutes per week. This results in an average of 11.8 machines that are constantly stopped because they have no input materials. These machines are ready to produce and thus staffed. This shows that there is a preceding process that limits the input of the curing department. Which of the preceding processes causes this limit is unknown.

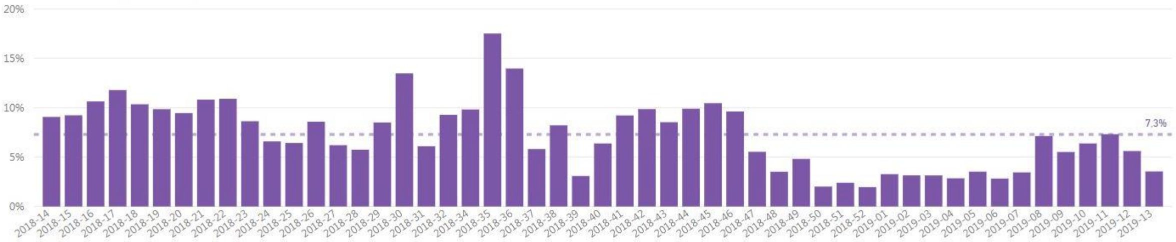


Figure 1.8: *Starvation time at the curing department per week (%).*

Apollo Vredestein wants to reduce the negative impact of the bottleneck on the throughput. They want to achieve both lower costs per tyre and a higher throughput. In Chapter 3 we elaborate on different operations management philosophies that are known in literature to improve manufacturing performance. In comparison to other philosophies, Theory of Constraints (TOC) has the advantage of defining a prioritization of improvement within the process. Also, Apollo Vredestein wants to implement the concept of TOC in the organization as a mind-set for continuous improvement. Thus, we decide to improve performance by following the TOC concept. We discuss this concept more extensive in Section 1.4, after we discuss the theoretical background of bottlenecks.

1.3 Bottleneck

There are numerous definitions of bottlenecks described in literature. All definitions agree to the fact that the bottleneck has a negative impact on the output of the production system. The negative impact is commonly described as: “constraining the system”. A few of these definitions are:

- Processes that limit output (Krajewski, Ritzman, & Malhotra, 2009).
- Processes whose isolated production rate has the highest sensitivity of the system’s performance compared to all other processes (Kuo, Lim, & Meerkov, 1996).
- The stage in a system that has the largest effect on slowing down or stopping the entire system (Roser, Nakano, & Tanaka, 2004).

Roser and Nakano (2015) expand these definitions to include both multiple bottlenecks and a measure of influence on the system:

“Bottlenecks are processes that influence the throughput of the entire system. The larger the influence, the more significant is the bottleneck.” (Roser & Nakano, 2015)

Bottlenecks in dynamic systems are not stable as they can shift due to machine downtime such as faults or preventive maintenance. A *shifting bottleneck* means that the location of the bottleneck changes over time. The more balanced the system, the more the capacity of all parts within the system is the same. This increases the influence of temporary downtime on the location of the bottleneck. Thus, the more balanced the system, the more probable it is that the bottleneck will shift. These shifting bottlenecks are the system’s constraint for only a certain period of time, so they are *momentary bottlenecks*. It can occur that the high level of balance within a system results in a different bottleneck every minute. This is called a *continuously shifting bottleneck*.

There are two types of bottlenecks. *Short-term bottlenecks*, also called momentary bottlenecks, are caused by temporary problems. For instance, an employee who becomes ill and the work cannot be done by someone else. This causes a backlog of work until the person is back. Or, an accident at a machine can lead to an unplanned stop. This also causes a backlog of work until the situation is resolved and the machine is turned back on. *Long-term bottlenecks* are blockages that occur regularly. For instance, general inefficiency of a machine. Both short-term and long-term bottlenecks can shift over time, which results in multiple bottlenecks. Each bottleneck has a certain amount of influence on the throughput of the entire system. The bottleneck with the largest influence is the *most significant bottleneck*.

Furthermore, bottlenecks can be *internal* or *external* to the system (Cox III & Schleier, 2010). An internal bottleneck occurs when the market demands more from the system than it can deliver. If this is the case, we deal with an operational bottleneck and the focus of the organization should be on identifying and improving the bottleneck within the system. An external bottleneck exists when the system can produce more but cannot sell it. This can be a market constraint or a sales process constraint. If this is the case, then the focus should be on creating more demand.

In complex and dynamic systems, it is expected that there are multiple bottlenecks. We cannot look at all the bottlenecks at once, thus we start with analyzing the most significant one. The bottlenecks can move over time, because of improvements, changes in demand, etc. If there is a new most significant bottleneck, we want to determine the location of that bottleneck. Thus, we want to be able to continuously monitor and identify the bottlenecks. Section 1.4 elaborates on Theory of Constraints: a concept that continuously analyzes the bottleneck. The identification of the bottleneck is a part of this concept.

1.4 Theory of Constraints

In the seventies, Eliyahu Goldratt criticized the operations management methods that were used in that time and work as if it were true that “optimizing each part of the system causes the system as a whole be optimized”. Goldratt developed a new method, called Theory of Constraints (TOC). Goldratt and Cox convey the concepts of TOC in the book *The goal* (Goldratt & Cox, 1986). This management concept recognizes that there are limitations to the performance of a system caused by a very small number of elements in the system. TOC emphasizes a five steps process of ongoing improvement, see Figure 1.9.

- STEP 1: Identify the system's constraint(s), also called bottlenecks. Constraints may be physical (e.g. materials, machines, people, demand level) or managerial.
- STEP 2: Exploit the constraint(s). We decide how to optimize the system's constraint(s). The goal is to achieve the highest throughput possible at the constraint(s) with the system's resources.
- STEP 3: Subordinate everything else to the above decision, i.e. adjust the other processes to support the constraint(s). Because constraints determine a firm's throughput, having the right resources at the right time at the constraint is vital. Thus, every other process in the system (i.e. *non-constraints*) must be adjusted to support the maximum effectiveness of the constraint. If the effectiveness of the constraint increases, so does the effectiveness of the system. Any resource produced that is not needed will not improve throughput but will increase unnecessary inventory. Thus, the other processes should support the constraint, but should not overproduce.
- STEP 4: Elevate the constraint(s), i.e. improve the system's constraint(s). If the existing constraints are still the most critical in the system, capacity can be added. Eventually, the constraint is broken and the system will encounter a new constraint.
- STEP 5: Prevent inertia. If in any of the previous steps a constraint is broken, go back to Step 1.

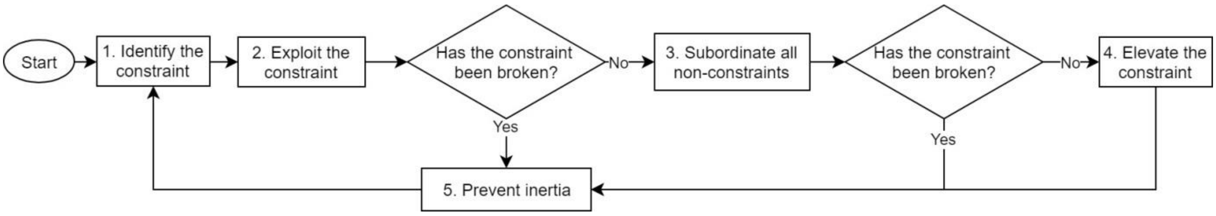


***Figure 1.9**: Flowchart of the five steps of ongoing improvement.*

Operational performance measures defined by TOC are *throughput*, *inventory* and *operating expense*. According to TOC, throughput is the rate at which the system generates money through sales. Thus, output that is not sold is not throughput but inventory. Inventory is all money invested in things the system intends to sell. Finally, operating expense is the money spent turning inventory into throughput. This includes expenditures such as direct and indirect labor, supplies and outside contractors.

The steps of ongoing improvement facilitate the successful execution of a TOC implementation. Therefore, we use these steps as a guideline for this research.

1.5 Research objective

Project objective: Create a dashboard to support the first step of the TOC cycle: identify the bottleneck. Also, find the causes of the most significant bottleneck for the current situation and create a solution accordingly to increase the throughput. Finally, align other processes to support the bottleneck.

Remarks:

1. This project is part of a bigger project where the goal is to increase the throughput (the number of tyres produced according to sales plan), while lowering operational expenses and inventory for both PCT as SM & AGRI by following the concept of TOC.
2. The research objective includes step 1 to 3 of the TOC cycle of ongoing improvement. The dashboard is a tool that can be used when this cycle is repeated in the future. The dashboard will aid Apollo Vredestein to perform step 1 “Identify the system’s constraint(s)” of the TOC cycle of ongoing improvement. Thus, the dashboard will help identify the bottleneck using the data. Step 2 to 5 cannot be performed using only data and the knowledge of the performer. Therefore, Apollo Vredestein will have to independently perform these steps in the future.

1.6 Organizational structure

Figure 1.10 represents the production at Apollo Vredestein which consists of roughly five stages. These stages can differ slightly per sector, as explained below. The first stage is mixing where a rubber compound is formed by mixing rubber and a certain combination of chemicals. Next, the rubber is processed at the second stage, semi-finished products. In this stage the rubber is processed into components by means of extrusion, calendaring and cutting. The third stage, assembly, collects the components needed and starts building the tyre. The assembled tyre is called a greentyre. The greentyre moves to the fourth stage, curing. Here, the greentyre is vulcanized, or cured, by applying heat and pressure in special machines to produce the finished tyre. The last stage differs per sector and can be uniformity, mounting or both. For PCT, the last stage is limited to uniformity and includes the inspection of the final product. For SM, the last stage is limited to mounting and includes putting the tyres onto the wheels. AGRI can have none, one or both of these steps. If requested by the manufacturer, OE tyres (AGRI) can go to uniformity. Also, some of the tyre types (AGRI) go to mounting. Section 2.2 gives a more detailed description of the production process. To manage the five stages, also called departments, Vredestein has six business teams and there are some additional teams to support the production, such as Industrial Engineering, Product Industrialization, Plant Engineering, and Quality Assurance & IT.

Figure 1.10: *The five stages that roughly form the production.*

PCT largely has its own production process and is limited by the demand from the market. This means that the bottleneck is external, i.e. the market. AGRI and SM share more machines and are both limited by the production capacity, i.e. the bottleneck is internal. As PCT and AGRI/SM share less machines, we treat PCT as a separate production process.

1.7 Root cause analysis

To get an understanding of the problem and its causes, we perform a root cause analysis in which we create a problem tree for the main problem: limited throughput of the system. Figure 1.11 represents the problem tree. Limited throughput can be caused by an internal or external bottleneck

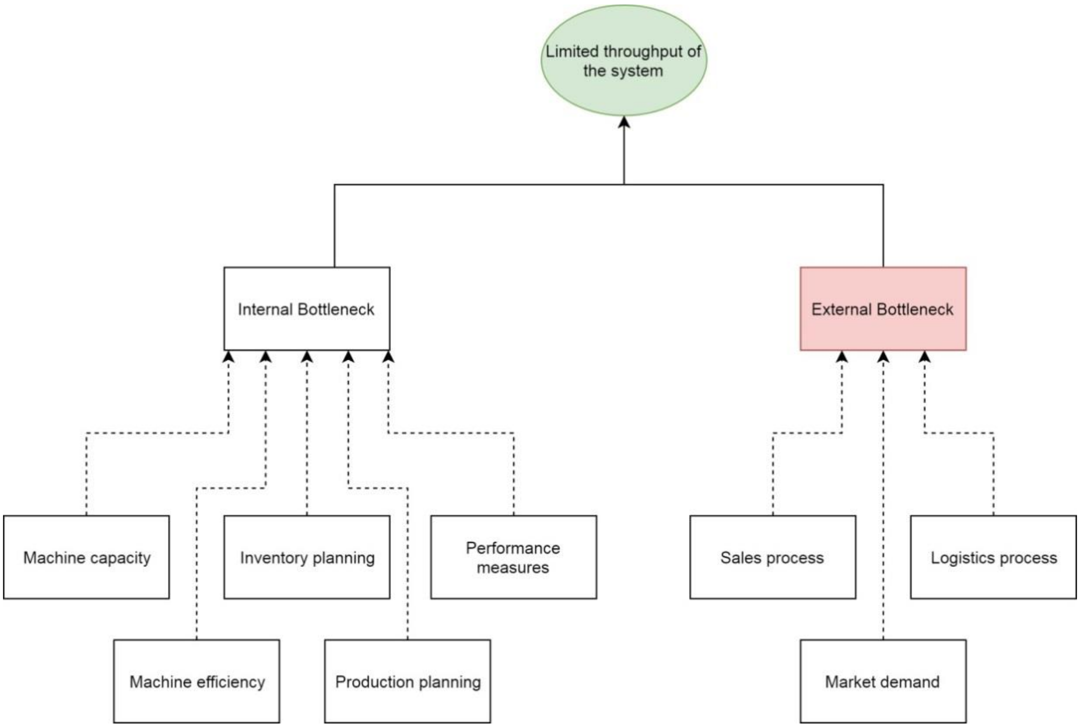


Figure 1.11: *Problem tree.*

(see Section 1.3). As explained in Section 1.6, both types are present within Apollo Vredestein and differ depending on the product line. PCT has an external bottleneck, and AGRI and SM have an internal bottleneck. The external bottleneck is always a process and has a large impact for PCT. In the past, the system has been able to produce 18,000 tyres a day. Nowadays, this number is set to 12,000, because of the external bottleneck. Of course, resources such as manning have been adjusted to this change. Thus, the system is able to increase its throughput if necessary, but it will require some changes. The internal bottleneck can be a machine or a supporting process. It is expected that there are multiple bottlenecks (see Section 1.3). There is always at least one bottleneck machine, and there can be no, one or more bottleneck processes. Below, we explain the branches of the tree for both the internal and the external bottleneck.

If there is an internal bottleneck, the bottleneck has to be identified first to be able to analyze the causes. Therefore, at this point we cannot complete the tree. Some broad possible causes are displayed with dotted lines. The first possibility is machine capacity. This means that the machine capacity might not be enough to fulfil the demand and thus constrains the throughput. The second possibility is machine efficiency. If the machine efficiency is low, the machine has many losses, which lead to less time to produce. If the machine needs that time to produce, it results in being the bottleneck. The third possibility is inventory planning. Frequently it is not exactly known what the inventory level of semi-finished products should be within production. Inventory can be a reason for a machine to become the bottleneck, if the physical inventory is not the right inventory. The fourth possibility is production planning. In the current situation the production planning is based on the desired output of the curing department. This makes curing the leading department in the production planning process. Thus, it does not take the bottleneck into account, which can create erratic flow and congestion. An adjusted planning system could be necessary to improve the performance of the bottleneck machine. Finally, the fifth possibility is performance measures. The current key performance indicators (KPIs) for each sub process lead to local efficiencies. In order to stimulate behavior to create an efficient overall process, new KPIs could be necessary that stimulate global efficiencies. Also, the current local KPIs are not supporting the production planning. Because of this, the production planning is regularly not followed correctly. This means that (without consulting a planner) either too many or too few units are produced in comparison to the production planning. This can lead to losses at the bottleneck machine.

An external bottleneck can have multiple causes. Figure 1.11 displays some broad possible causes with dotted lines. An external bottleneck is always outside of the plant, i.e. the production area. The production area includes all processes that directly influence the production. Thus, the production area includes for instance the machines, machine schedules, and intermediate stock levels. The production area excludes all processes that determine what part of produced products is sold. Thus, the production area excludes for instance demand forecasting, sales and logistics outside the plant. These processes are included at the headquarter. We conduct this research at the plant. This concludes that an external bottleneck is not something the plant can control and following the methodology of Heerkens & van Winden (20012) we do not consider this the core problem.

1.8 Research scope

This research focuses on increasing the throughput by implementing the TOC concept. We should focus on the core problem (Heerkens & van Winden, 2012), therefore the external bottleneck is out of scope, see Section 1.7. Thus, we choose to focus on the bottleneck within production, the internal bottleneck. The core problem of the internal bottleneck can be defined after the bottleneck is identified. Focusing on the internal bottleneck means that we look only at the production process for AGRI and SM. While identifying the most significant bottleneck we focus on the most significant bottleneck machine and leave out the bottleneck processes, because of the following. There is at least one bottleneck machine. It does not necessarily have to be the most significant bottleneck, because a bottleneck process can be the most significant bottleneck. However, if there is a bottleneck process, it is most likely also influencing the throughput of the bottleneck machine. This means that a bottleneck process becomes visible during the analysis of the bottleneck machine as a cause of limited throughput at the bottleneck machine. If the influence of the bottleneck process is big, the problem will be dealt with in step 2 of the TOC cycle. This decision increases the reusability and the feasibility of a dashboard supporting the identification phase, while taking all internal bottlenecks into account. Thus, we focus on identifying the most significant bottleneck machine.

Also, the last stage of production called uniformity & mounting is left out of the scope. This is the last production step that is executed outside of the plant, for both AGRI and SM. Also, it is known that Vredestein cannot meet the demand at the curing department, see Section 1.2. Thus, there is a limiting process in the preceding processes of the curing department. Because the last stage is executed outside the plant and we know there is a bottleneck within the plant, we leave it out of the scope.

As explained in Section 1.3, we expect multiple bottlenecks in complex and dynamic systems. We cannot look at all the bottlenecks at once, thus within this research we focus on the most significant bottleneck and exclude other bottlenecks.

To reach the project objective, we go through steps one to three of the cycle of ongoing improvement. Apollo Vredestein wants to explore the options of improvement without big investments. Also, due to the time limit we do not repeat the cycle. Therefore, steps four and five are out of scope.

1.9 Research questions

From the research motivation, objective and scope the following main research question follows:

"How can Apollo Vredestein identify the most significant bottleneck machine within the production line of agricultural and space master tyres, improve the most significant bottleneck machine, and align non-bottleneck machines to increase the throughput of the system?"

To be able to answer the main research question, we formulate multiple research questions. First, we gain information about the situation of Apollo Vredestein to be able to choose the right method and identify possibilities to reduce the negative impacts of the bottleneck. We research the production process and the production flow. Next, to be able to optimize the bottleneck we find out what drives the production. How is the production planning made? How does Vredestein use and plan intermediate stock? What is the current performance of the system? Also, to answer research question 3e, we research the current way of managing wrapping material. This results in the first set of research questions:

1. Current situation
    a. How does the production process flow?
        i. What is the tyre structure?
        ii. What is the production process?
    b. How is the production planned?
    c. How is intermediate stock planned?
    d. What is the performance of the system?
    e. How is wrapping material managed?

After obtaining knowledge about the current system, we research operations management philosophies proposed in literature that improve the manufacturing performance. Next, we find out what is already known in literature about bottlenecks. As we already specified the meaning of the bottleneck in Section 1.3, we now focus on the identification of the bottleneck. Also, to answer research question 3e, we review literature about inventory control and inventory control policies. This forms the second set of research questions:

2. Literature review
    a. What are the known philosophies for improving performance?
    b. What are the known bottleneck detection methods?
    c. What is the objective of inventory control?
    d. What are the known inventory control policies?

The third set of research questions covers the model framework. We decide which bottleneck detection method is suitable for Apollo Vredestein and develop a bottleneck identification process. Next, we determine an approach to make an overview of all efficiency losses of the current bottleneck and decide how to determine which efficiency losses are important to analyze. Finally, we decide how to reduce the amount of shortage of wrapping material, which is the focus of improvement that results from research question 4b. This results in the third set of research questions:

3. Model framework
    a. Which bottleneck detection method is suitable for Apollo Vredestein?
    b. How can we design the bottleneck identification process?
    c. How can we make an overview of all efficiency losses of the current bottleneck?
    d. How can we determine which efficiency losses are important to analyze?
    e. How can we reduce the amount of shortage of wrapping material?
        i. How can we obtain a good representation of the real inventory of wrapping material in the system?
        ii. Which inventory control policy is suitable for wrapping material at Apollo Vredestein?

Next, we execute the model framework. Using the bottleneck identification process, we identify the current most significant bottleneck. We conduct a root cause analysis to find a focus of improvement for the bottleneck. The focus of improvement leads us to researching the average length and variation in length of a roll of wrapping material as well as to assessing the performance of the inventory control policy. To do so, we use the fourth set of research questions:

4. Model implementation
    a. What is the current most significant bottleneck machine?
    b. What is the root cause?
        i. What are efficiency losses of the current bottleneck?
        ii. Which of these losses are important to further analyze?
    c. What is the solution to increase the reliability of booked inventory for wrapping material fits Apollo Vredestein?
    d. What is the performance of the inventory control policy for wrapping material?

Now, we can make a recommendation to Apollo Vredestein that answers the main research question: *"How can Apollo Vredestein identify the most significant bottleneck machine within the production line of agricultural and space master tyres, improve the most significant bottleneck machine, and align non-bottleneck machines to increase the throughput of the system?"* Table 1.1 shows the thesis outline to give an overview of the research questions and their corresponding chapter.

Table 1.1: *Thesis outline.*

Chapter number	**Chapter title**	**Research questions**
Chapter 2	Current situation	*Questions 1a-1e*
Chapter 3	Literature review	*Questions 2a-2c*
Chapter 4	Model framework	*Questions 3a-3e*
Chapter 5	Model implementation	*Questions 4a-4d*
Chapter 6	Conclusion	

2. Current situation

This chapter answers research question 1 “What is the current situation?”. Sections 2.1 and 2.2 explain respectively the tyre structure and the production process. Section 2.3 shows the production flow for both AGRI and SM. Next, Sections 2.4, 2.5, and 2.6 discuss respectively the production planning, intermediate stock, and system performance. Finally, Section 2.7 gives more in depth information about wrapping material, because this is linked to the chosen focus of improvement in Section 5.2.

2.1 Tyre structure

A tyre consists of several components. In this section a general overview of the components and tyre structure is given as described in “The Unofficial Global Manufacturing Trainee Survival Book” (Apollo Vredestein B.V., 2015). The tyre structure consists of several different layers. The structure can vary for the different tyre types, Figure 2.1 shows an example of the different parts that make up a tyre. We describe the components below.

- Tread: The part of the tyre that is directly contacting the road surface.
- Sidewalls: Provide lateral stability and prevents air from escaping and keeps the body plies protected.
- Beads: Rubber-coated steel cable whose function is to ensure that the tyre remains attached to the wheel rim.
- Body plies (Also known as carcass or carcass plies): A main part of the tyre that is in the form of a layered sheet consisting of polyester, nylon, or wire thread with rubber liner that supports the tread and gives the tyre its specific shape.
- Inner Liner: A sheet of low permeable rubber laminated to the inside of the first casing ply of a tubeless tyre to insure retention of air when the tyre is inflated.
- Steel Belt: It is made of steel and is meant to provide reinforcement to the section that is directly underneath the tread.
- Cap Plies: The cap plies are much like the steel belts, except that the sheets are composed of woven fibres. These inelastic plies help to hold the tyre’s shape and keep it stable at high speeds.

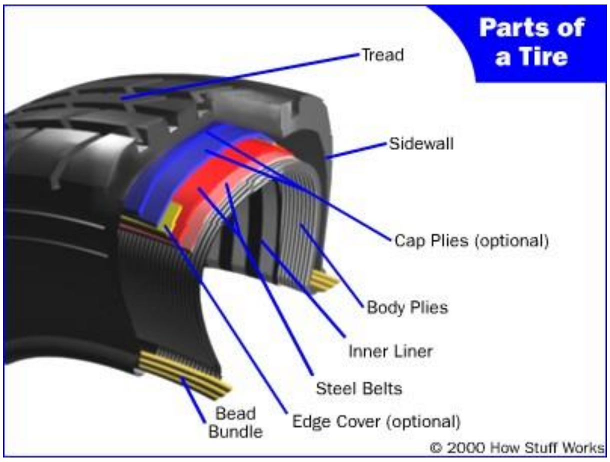


Figure 2.1: *Tyre structure. Reprinted from “The Unofficial Global Manufacturing Trainee Survival Book”, by Apollo Vredestein B.V., 2015.*

2.2 Production process

As already mentioned in Section 1.6, the production consists of roughly five stages: mixing, semi-finished products, assembly, curing and uniformity & mounting. This section discusses these five stages that form the production process as described by Apollo Vredestein (2015). Processes including heat treatment deliver rubber that needs an *aging period* before it can be processed in the next production step. We define the aging period as the time the rubber needs to get the pre-specified properties.

2.2.1 Mixing

A rubber compound is formed by mixing rubber, carbon black, sulphur and other materials using gigantic mixers. Additional heating and friction are applied to the batch to soften the rubber and evenly distribute the chemicals. The chemical composition of each batch depends on the tyre part. So certain rubber formulations are used for the body, other formulas for the beads, and others for the tread. Although it sounds simple, mixing is actually quite complicated and has to be done several times. Figure 2.2 represents the mixing process.

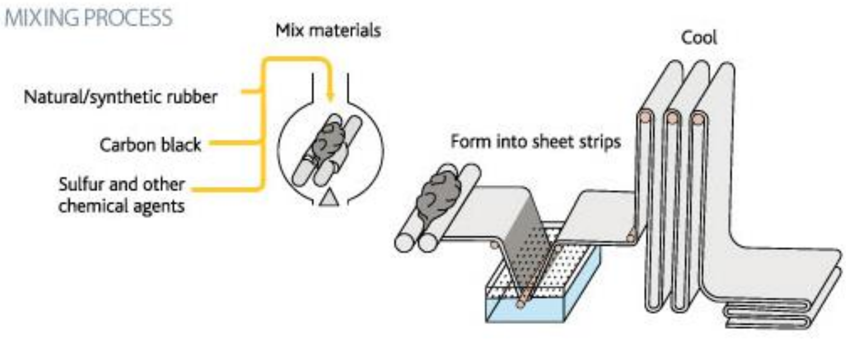


Figure 2.2: *The mixing process. Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", by Apollo Vredestein B.V., 2015.*

2.2.2 Semi-finished products

The stage semi-finished products consists of extrusion, calendaring and the bead-making process. During extrusion the batch is further mixed and heated and is then forced out through a die to form a layer of rubber. Figure 2.3 shows the extrusion process.

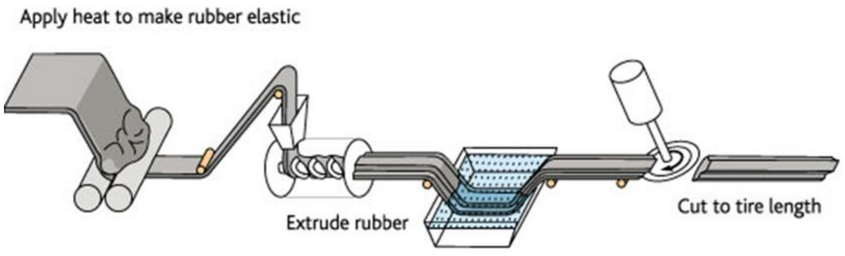


Figure 2.3: *The extrusion process. Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", by Apollo Vredestein B.V., 2015.*

Calendaring includes a series of hard pressure rollers used to form or smooth a sheet of material. Afterwards, it is cut at a proper angle into a specific length and width. The sheets that are cut are adhered by means of heat and form a roll of material with the specific measures. Figure 2.4 shows the calendaring and cutting process.

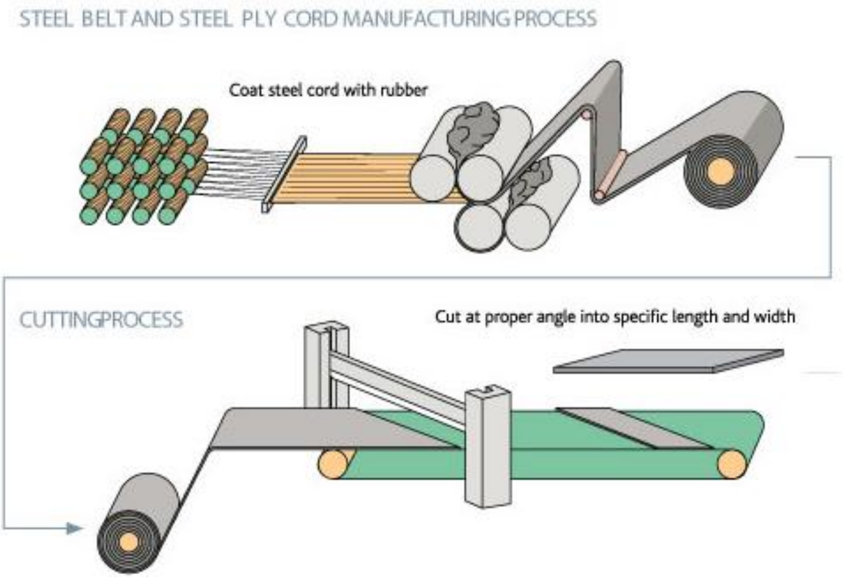


Figure 2.4: *The Calendaring process. Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", by Apollo Vredestein B.V., 2015.*

Finally, the bead-making process starts with a bead core. The bead core is made of steel and is rubber coated by extrusion. Figure 2.5 depicts the bead making process. Additionally, some beads require a coating of wrapping material around the bead core. The bead is completed when the bead filler is extruded and applied to the bead. The completed beads are placed on a rack ready for assembly.

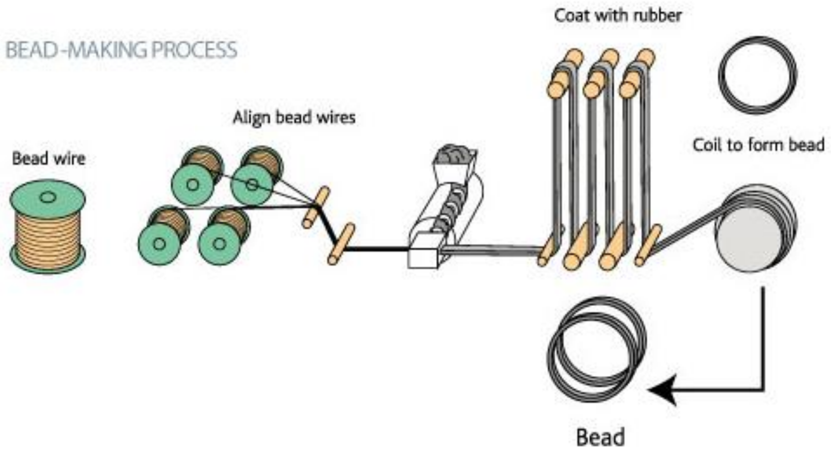


Figure 2.5: *The bead-making process. Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", by Apollo Vredestein B.V., 2015.*

2.2.3 Assembly

The tyre is built on a Tyre Building Machine (TBM), which is the "workbench" in which all the components are assembled in order to make up what is known as a 'green' tyre. The tyre is built inside out, so the inner liner, body ply, bead with bead filler, sidewalls, belts and tread are assembled in sequence. Figure 2.6 shows the building process. In order to fully understand this figure, it is important to note that a carcass is a horseshoe-shaped inner lining of a tyre and is made up of a number of layers of textile cord plies.

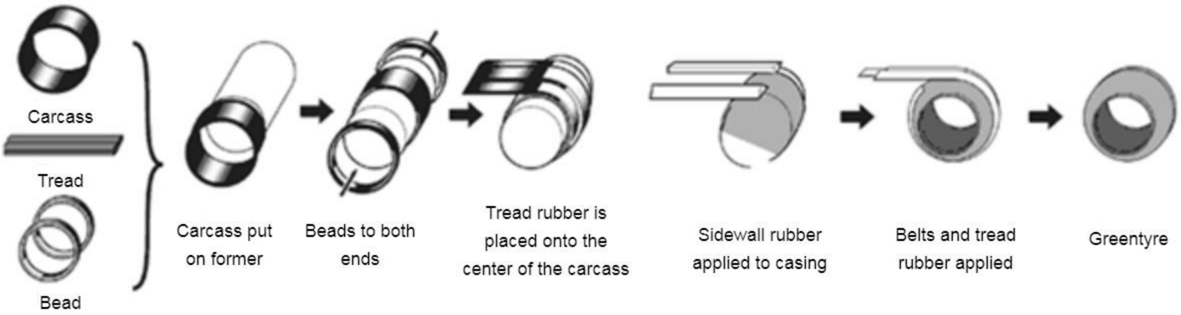


Figure 2.6: *Greentyre Assembly. Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", by Apollo Vredestein B.V., 2015.*

2.2.4 Curing

The greentyre must be vulcanized, or cured, by applying heat and pressure in special machines to produce the finished tyre. During vulcanization, the greentyre is placed in a curing mold and is subjected to intense pressure and adequate heat internally and externally for a specified period of time. Once the process is finished it is transformed into a tough road-worthy tyre. Figure 2.7 represents this transformation.

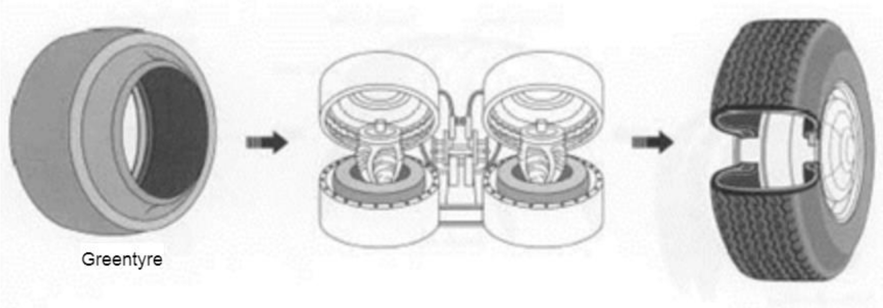


Figure 2.7: *The curing process. Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", by Apollo Vredestein B.V., 2015.*

2.2.5 Uniformity & Mounting

Afterwards, if it is requested by the manufacturer, OE tyres in the sector AGRI go to uniformity. Here the tyres are inspected visually and with automated inspection machines that detect the slightest defect on the final product. All SM tyres and some types of AGRI tyres go to mounting. Mounting tyres means putting the tyres onto the wheel rim.

2.3 Product flow

After knowing the production process, we make flow charts to visualize the product flow. We repeatedly discuss temporary charts with multiple employees to generate the flow charts. The product lines AGRI and SM share multiple machines and we want to identify the bottleneck for both product lines. Thus, we map all the relations that the machines have with each other. For the readability of the flowchart, we leave out the distinction between component flows. Figure 2.8

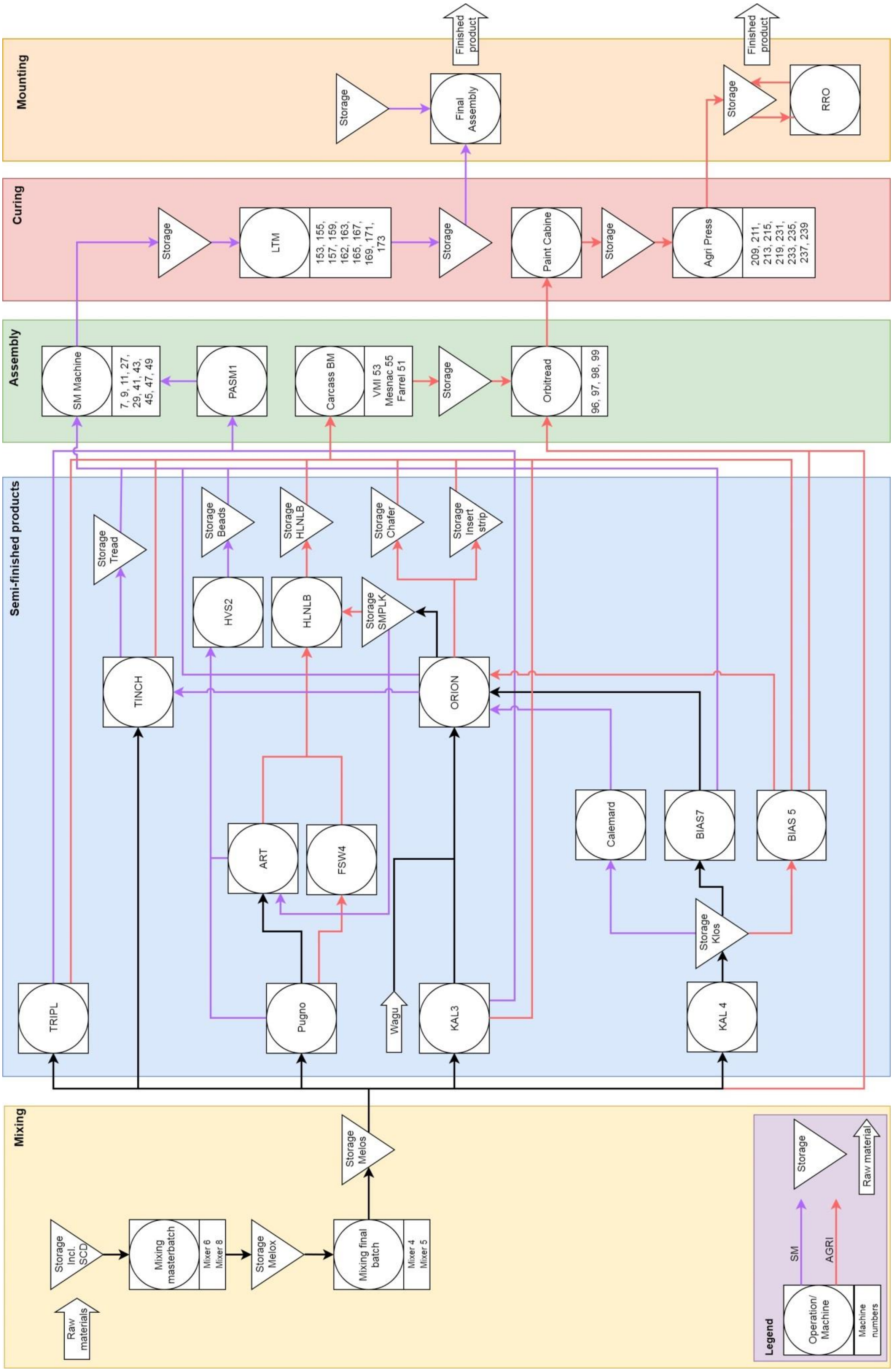


Figure 2.8: *Combined process flow for both AGRI and SM.*

represents the flowchart for AGRI and SM. Here, the red arrows represent the AGRI line, the purple arrows represent the SM line and black arrows indicate that both lines travel in that direction. There are multiple components per product line that follow different routes, which means that multiple arrows (from the same product line) can leave an operation/machine or storage. We divide the columns in the production stages from Figure 1.10. These flow charts include the stage uniformity & mounting for transparency even though they are out of the scope. The flowchart contains names that are not important for the reader. These names are how employees at Vredestein call the operations, machines or storage places. If there are multiple machines that execute the same operation, they are indicated in the cell below the operation. For instance, there are two machines, Mixer 6 and Mixer 8, that execute the operation called mixing masterbatch. If there is only one machine to execute an operation, the name in the flowchart refers to the machine name and there is no cell below the machine. Also, we look at the flowcharts with distinction between component flows. For the readability of the flowchart, we make separate flow charts per product type (AGRI/SM), see Appendix 1. Here, the column “semi-finished product” contains flows for different components that are presented with a specific arrow layout to develop understanding of the flow per component.

2.4 Production planning

Vredestein uses *material requirements planning (MRP)* as a production planning, scheduling and inventory control system to manage their manufacturing processes. MRP is a *push system* since it computes schedules of what should be started (or pushed) into production based on demand (Hopp & Spearman, 2011). The process starts with a request from sales. A request from sales is usually based on a forecast (make-to-stock), but can also be based on an order (make-to-order). Sales has an annual plan containing all order quantities per time period for all end items (i.e. tyre types). The annual plan is known in literature as the *master production schedule (MPS).* It gives the quantity and due dates for all demand of finished products. The MPS is updated throughout the year with new information. MRP uses this information to obtain the gross requirements that initiate the MRP procedure. MRP works backward from the MPS to derive schedules for the components. The *bill of materials (BOM)* specifies the relationship between the end product and the components. Using the BOM, a curing plan is based on the MPS, a building plan is based on the curing plan, etc. There are exceptions for processes that have a long lead time. The exceptions are the purchase of raw material and orders for mixtures. The purchase of raw materials is based on the MPS. As suppliers have a long delivery lead time, the plan is made far ahead of time, matching the delivery lead time. The order for mixtures is based on the curing plan. The mixing department delivers rubber that needs an aging period before it can be processed in the next production step. The aging period makes mixing a production process that is not flexible. This results in the mixing plan being based on the curing plan and not on the succeeding process. To account for uncertainty and randomness they use a safety lead time. Applying a safety lead time means that the material should be delivered a certain amount of time prior to when it is scheduled for usage. The safety lead time is set per department and therefore not component specific. Figure 2.9 represents the information flow concerning the planning as described above.

PIBS (Productie Informatie en BesturingsSysteem, which translates to production information and operating system) is a system provided by the ICT department and it is used to manage many

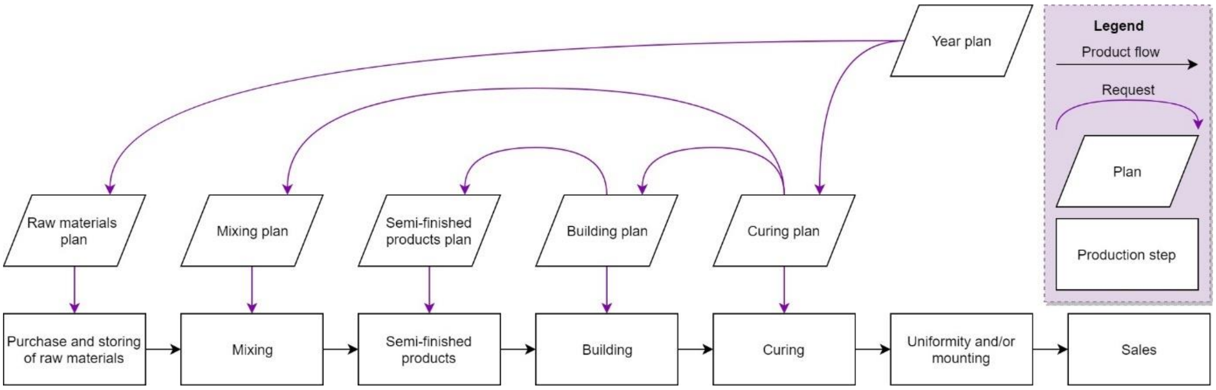


Figure 2.9: *Information and product flow with regard to the planning. Adapted from "Plannings-optimalisatie van de productieplanning van Apollo Vredestein B.V.", by Cornelissen, J., 2019.*

processes in the plant. Among other things, the MRP is made in PIBS. A request is registered into PIBS as an amount of tyres of type *x* to be finished on date *t*. PIBS then calculates throughout the system what resources are needed at each step of the production process to be able to finish this on time. This means that in the planning, curing is seen as the bottleneck and the other plans are based on the desired output from curing. PIBS communicates the planning to the machines or operators, and it contains all product specifications. PIBS is also used to document historical production data. Thus, after every shift of eight hours the amount of tyres produced and the losses occurred (in minutes per category) are documented. Then, the plan is revised with the information of the past 8 hours.

To determine the amount of tyres that can be produced in a shift the *standard time* is used. Within Apollo Vredestein standard time is defined as: "the time required to produce a qualitative (specified per product) good product at a workstation with the following conditions:

1. A qualified, average skilled operator working in normal pace,
2. Working on operational released equipment according technical specifications
3. Doing a specific task/s by using pre-scribed tools and following valid standards"

The standard time consists of the *machine cycle time* and *frequential time*. The machine cycle time is the sum of all cyclical activities, i.e. activities that are always executed at that station to manufacture each product. The frequential time is the time of the activities not performed in all cycles, but in a certain frequency (such as the exchange of cassettes), and are part of the process. The frequential time is partially calculated by multiplying the time of the activity by its frequency and partially by applying a correction rate(%) for unaccounted delays or activities.

2.5 Intermediate stock

PIBS also tracks intermediate stock for some SKUs. Thus, it is possible to monitor the current inventory of a certain SKU within PIBS. This is managed by scanning SKUs after certain activities. Picking up and delivering SKUs is registered to keep track of the location of the SKUs. At the machine, using a SKU and the amount that is left over from using a SKU are scanned to make sure the available stock in the plant is the same as in the system. The other SKUs that are not tracked are also registered in the system, but the location of these items is not available.

Depending on the type of product, SKUs are stored at an intermediate stock or directly transported to the next machine. The safety lead time, aging period, and batch size generate a need for storage space. Thus, the stock that is available consists of SKUs that are ready *x* hours (i.e. the safety lead time) before they are needed in production and SKUs that have an aging period. The exception is the stock of mixtures and the stock of calendar rolls. Large amounts are produced in successive batches to reduce the amount of waste. This means that the minimum amount produced is larger than the amount defined by the orders. Thus, the stock level is defined by large residues from production runs and order related SKUs. The triangles in the flowchart from Figure 2.8 represent all intermediate stock. If there is no intermediate stock in the flowchart it means that each subsequent machine has its own (small) storage place. There are two storage spaces for a specific machine registered in PIBS as separate intermediate stock, because they are bigger storage spaces. This the stock in front of the ORION and VPA (SM preassembly). Figure 2.8 does not present those stocks, because they are linked to a specific machine.

Currently, the business teams strive to have a certain amount of production hours (equal to the safety lead time) in stock. This is defined as a total and does not specify the variety of the stock. There is a maximum level of stock defined by the space available, by a self-defined limit or by the material handling equipment (MHE). Many products use specific MHE, which means that if all MHE of a specific product is occupied, no new products can be produced.

2.6 System performance

The system performance regarding TOC can be measured by the percentage of time that there are no greentyres (NGT) at the curing department. As we mentioned in Section 2.4, Apollo Vredestein plans on the curing department, which means that all starvation losses at curing result in lost tyres that could have been sold. NGT is the only starvation loss that occurs at the curing department. Thus, a low percentage of NGT reflects a good performance of the system. Figure 2.10 gives an overview of the starvation time (NGT) at the curing department per week for AGRI and SM (%). The time frame of the figure corresponds with the time frame that we use in Chapter 5 to perform the bottleneck identification. The average starvation during that period at the curing department was 8.5%. This means that on average 8.5% of the time that a machine in the curing department is available, it cannot produce because it has no input materials. The starvation per week for all machines varies between an average of 2.8% and 14.0%. The division of starvation among the machines in the curing department is currently unknown, because they are booked as one group of machines.

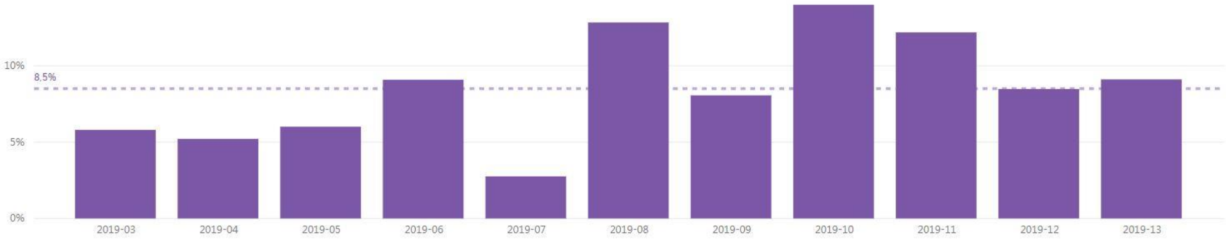


Figure 2.10: *Starvation time at the curing department per week for AGRI and SM (%).*

A lower NGT percentage can mean three things. First, the throughput of the system has increased. The building department delivers more tyres at the right time. This turns a part of the time a machine is idle into time the machine is producing. Thus, the throughput of the system increases. Second, the planning is adjusted to the bottleneck. The curing department lowers their demand, making it possible for the building department to deliver more tyres (%) at the right time. Thus, the NGT percentage decreases. This results in a more realistic demand throughout the plant, improving the flow. Over-demanding the system results in more rush orders and changeovers disturbing the planning. In practice that means that an improved flow also leads to an increase in throughput. Third, the decision is made to use operators from the curing department to focus on another part of production. This decision is only made if another process has a large breakdown or other issues that are expected to lead to large shortages at succeeding processes and finally starvation at the curing department. This decision will lower the NGT and result in the highest possible throughput in that situation. Thus, all three possibilities that result in a lower NGT are positive for the throughput of the system. In theory, a lower NGT can also be accomplished by adjusting the planning below the capacity of the system. In practice, this will never happen, because Vredestein steers on the MPS and numbers produced.

2.7 Wrapping material

Wrapping material is a small strip of rubber that is used to coat the bead core (see Section 2.2.2). Figure 2.11 shows what a roll of wrapping material looks like. Wrapping material is produced at a machine called the ORION, which is present in the flowchart in Section 2.3. There are two types of wrapping material: HE01-00-0034 and HE01-00-0038. They are made from the same material, but the width of the wrapping material is respectively 3.4 and 3.8 cm. HE01-00-0034 and HE01-00-0038 are used for beads with respectively 16 and 24 steel wires in the bead core. The core of a roll of wrapping material, as depicted in Figure 2.11, is the material handling equipment (MHE). This forms a basis for rolling up the material and also makes it possible to store the material on a rack.

***Figure 2.11**: A roll of wrapping material.*

Demand

The demand of wrapping material is intermittent. This means that demand occurs on a somewhat infrequent basis. Depending on the SKU (bead) produced at the ART, there is a need for wrapping material. This means that a shift without demand can occur. Figure 2.12 represents the demand (in meters) for both types of wrapping material. Also, we have *advance demand information*, because

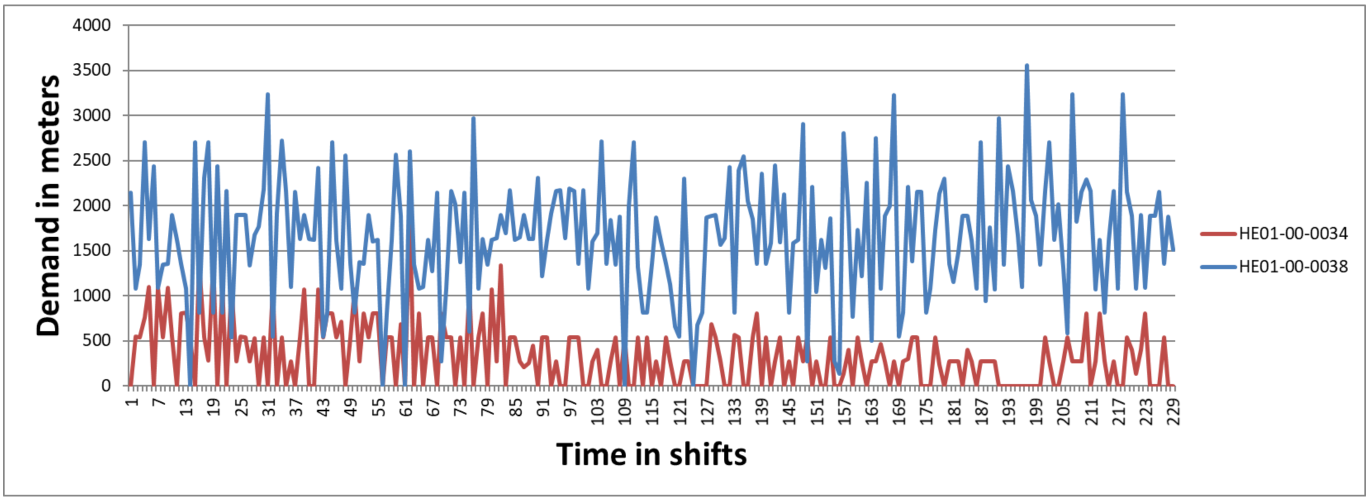


***Figure 2.12**: Demand per shift for HE01-00-0034 and HE-01-00-0038.*

the demand is created by Vredestein. Advance demand information for a product is obtained when customers place orders in advance for a future delivery (Özer & Wei, 2004). Thus, the demand requested in future period *t* is given prior to period *t*, where one period equals to one shift. This means that we do not have external demand uncertainty.

Order system

The wrapping material has a fixed order quantity. The material comes originally from the machine called KAL4, where the slaps of rubber are calendared. This is done in large batches, because there are large setup costs related to scrap. After KAL4, the large rolls (Calendar rolls) are cut in two at the machine called the Calemard and finally the ORION cuts the rolls in smaller pieces with a specific width resulting in the desired SKU. Because the rolls of wrapping material are cut out of half a calendar roll, the calendar roll defines the batch size that leaves the ORION. Thus, the ORION has a fixed order quantity that can be ordered multiple times. However, due to scrap at the calendar process the width of the calendar roll can vary slightly. Also, the length of the roll is influenced by scrap at the Calemard and ORION. The length of a roll varies among batches, but is usually the same for all rolls within a batch. Thus, the order quantity per roll is fixed and equals 250 meters, but the amount that the ORION delivers fluctuates. This is internal demand uncertainty, which we explain in Section 3.3.1. When an order is placed, there is a lead time of 4 to 8 hours depending on the queue waiting time. This is internal supply uncertainty, which we explain in Section 3.3.1. The ORION produces for multiple machines, which creates fluctuations in lead time depending on the schedule. There is no agreement or contract on the lead time, because it is within Vredestein. If necessary, the wrapping material can be ordered with emergency. In case of emergency, there is a lead time of one hour.

Inventory

Because there is a fixed order quantity, there usually is *cycle stock*. The cycle stock is a result of producing or ordering in larger quantities than one unit at a time. The amount of inventory that results from these batches is called cycle stock. Also, when ordering wrapping material a safety lead time of two hours is applied. This means that the material needs to be delivered two hours prior to when it is scheduled for usage. This creates an amount of stock depending on the demand. The two-hour safety lead time is a general safety lead time applied to all orders in the semi-finished products department. Thus, it is not based on the uncertainties at the ORION. Furthermore, the wrapping material has a limited shelf life. The material has a shelf life of one month. If the material is older than one month, it has to be disposed of. The material is stored at the ART on a rack. There are two (different) racks that together can carry up to 126 rolls (of max. 250 meters) of wrapping material. For calculating the available storage capacity, we do not differentiate between HE01-00-0034 and HE01-00-0038, because the MHE has a width of 4.0 cm. Thus, the width of the MHE defines the storage capacity.

2.8 Conclusion

In this chapter we analyzed the current situation at Vredestein. In Section 2.1, we have given insight in the tyre structure and the components that are used to build a tyre. The production process is covered in Section 2.2 and consists of several steps. This section explains the departments and its processes that form the production process. To show how the production steps are linked to each other, we mapped the product flow in Section 2.3. To be able to produce they have to make a production planning, which we explained in Section 2.4. Vredestein uses material requirements planning (MRP) as a production planning, scheduling and inventory control system to manage their manufacturing processes. They add safety lead times to buffer against uncertainty. They use PIBS to manage all processes in the plant and among other things, the MRP is made in PIBS. We mentioned intermediate stock in Section 2.5. They also use PIBS to track inventory. The safety lead time, aging period and batch sizes generate a need for storage space. We described the performance of the system in Section 2.6. We can be measure the performance of the system with the percentage of no greentyres (NGT) at the curing department. In practice, a lower NGT percentage is positive for the throughput of the system. Finally, in Section 2.7 we gave more specific information for wrapping material about the previously mentioned topics.

3. Literature review

In this chapter we discuss some relevant findings in literature. Section 3.1 presents an overview of the main operations management philosophies to improve the manufacturing performance. Section 3.2 gives an overview of the bottleneck identification methods that are currently known in literature. Section 3.3 gives information about inventory control and the steps to systematically establish inventory policies.

3.1 Operations management philosophies

There are multiple operations management philosophies proposed in literature to improve the manufacturing performance. This section elaborates on the most common approaches: total quality management, business process re-engineering, lean manufacturing, theory of constraints and six sigma. This overview is based on the descriptions from Slack, Brandon-Jones, and Johnston (2016).

3.1.1 Total quality management (TQM)

This approach puts quality, and improvement generally at the heart of everything that is done by an operation. TQM achieves this by focusing on the following elements:

- Meeting the needs and expectations of customers
- Improvement covers all parts of the organization and every person in the organization.
- Including all costs of quality
- Getting things right the first time: designing in quality rather than inspecting it in.
- Developing the systems and procedures that support improvement.

3.1.2 Business process re-engineering (BPR)

BPR is based on the idea that, rather than using technology to automate work, it is better to remove the need for work in the first place. This can also be summarized as “do not automate, obliterate”. This approach strives for dramatic improvements in performance by radically rethinking and redesigning the process.

3.1.3 Lean manufacturing (LM)

The focus of lean manufacturing is to achieve a flow of materials, information and customers that deliver exactly what customers want, in exact quantities, exactly when needed, exactly where required and at the lowest possible cost. This is achieved by the elimination of waste in all its forms, the inclusion of all staff of the operation in its improvement and the idea that all improvement should be on a continuous basis. LM uses a *pull control*, where the pace and specification of what is done are set by the ‘customer’ workstation.

3.1.4 Theory of Constraints (TOC)

Theory of Constraints (TOC) focuses the attention on the capacity constraints or bottleneck parts of the operation. Here, a constraint is defined as anything that limits the system from achieving higher performance relative to its goal. TOC emphasizes a five steps process of ongoing improvement. One major assumption in TOC is that the measurements—throughput, inventory and operating expenses—can measure the goal of an organization, and everything else is derived logically from that assumption.

3.1.5 Six sigma (SiS)

Six Sigma is “A disciplined methodology of defining, measuring, analyzing, improving, and controlling the quality in every one of the company’s products, processes and transactions - with the ultimate goal of virtually eliminating all defects” (Slack et al., 2016). This comes from the idea that true customer satisfaction can only be achieved when its products were delivered when promised, with no defects, with no early-life failures and when the product did not fail excessively in service.

3.1.6 Discussion

All of the philosophies mentioned strive to improve the systems performance. Even though the approaches have the same goal, they do emphasize different type of changes. TQM, LM and TOC all incorporate ideas of continuous improvement, while SiS can be used for small or very large changes and BPR strives for radical changes. Also, they differ in the aim of the approach. For BPR the focus is on what should happen rather than how it should happen, while SiS and TQM focus more on how operations should be improved. The main contribution of TOC versus LM is the idea that the effects of bottleneck constraints must be prioritized and can excuse inventory if it means maximizing the utilization of the bottleneck. If demand is suddenly far greater than expected for certain products, the LM system may be unable to cope. Pull scheduling is a reactive concept that works best when independent demand has been levelled and dependent demand synchronized. While lean synchronization may be good at control, it is weak on planning.

3.2 Bottleneck identification methods

The term *bottleneck identification* refers to the research of where in the production line a process restrains the overall output. During the last decades, several bottleneck identification methods have been proposed in literature. These methods vary from analytical or simulation to data driven. Some of them are detecting a real-time bottleneck while most focus on a long-term bottleneck. Also, the system matching the method varies. In this section, we describe the most common methods known in literature.

3.2.1 Process time

This method measures the process times, or cycle time, and with that detects the capacity limit. In case of a flow shop, the machine with the longest cycle time would have the lowest capacity and therefore be the bottleneck (Kuo et al., 1996). This is a very fast and simple way to identify the bottleneck. The downside is that it does not include any losses or variability and therefore does not necessarily represent the true bottleneck. It merely shows the maximum capacity of the production line under ideal conditions. Also, this method works best for systems with one machine per station and constant cycle times.

3.2.2 Utilization

The utilization method knows multiple variations depending on the definition of utilization. For instance, Betterton & Silver (2012) define the utilization as the percentage of time the resource is not idle due to lack of work. Thus, utilization is calculated as the time spent producing divided by the effective process time, excluding setups or breakdowns. Because of this, it is also known as the *effective process time method*. On the other hand, Roser et al. (2003) define utilization as the percentage of time a resource is active. Here, active means that the resource is not waiting (i.e. working, breakdown, under repair, regular maintenance, changeover, etc.). Thus, utilization is calculated as the time a resource is active divided by the total time. All methods agree that in a serial line, the machine with the largest utilization is considered to be the bottleneck. As this method is based on averages it cannot detect shifting bottlenecks (see Section 1.3) in dynamic systems. The utilization method is comparable to the process time method, but it does take losses into account. The losses that are taken into account depend on the definition used. In contrary with the process time method, this method can be used on systems with varying cycle times because it uses aggregated times.

3.2.3 Inventory based methods

There are multiple methods that use the inventories between processes to detect the bottleneck (Roser & Nakano, 2015). This can be based on the queue length or the waiting time in queue. The *longest waiting time method* states that the station where work waits the longest is the bottleneck. This is measured by the maximum time a job spends in queue. The *longest queue method* identifies the station that has the greatest number of waiting jobs in queue for the largest proportion of the overall line processing period as the bottleneck. Both methods also have an average version, the *average waiting time method* and the *maximum average queue length*. Respectively measured by the average time a job spends in queue and the largest average number of waiting jobs in queue.

3.2.4 Arrow method

Li and Meerkov (2009) describe the arrow method that is based on *blockage and starvation probabilities*. Process blocking occurs when a process must stop because its subsequent buffer or process is full. This causes the preceding process to stop until the work in process (WIP) is cleared. Process starvation occurs when the preceding buffer or process is empty, meaning there is no supply of materials (Roser, Lorentzen, & Deuse, 2014). Thus, blockage probability is the percentage of the available time the machine is idle, because it has no production plan. This means that it has no order to produce or has reached a sufficient level of stock. Starvation probability is the percentage of the available time the machine is idle, because it is waiting for parts from upstream. If the machine blockage and starvation probabilities, respectively mb_i and ms_i for each station i, are known, this method can identify the location of the bottleneck in serial production lines.

If:

$$mb_i > ms_{i+1}: i = 1, \dots, M-1$$

Where M is the number of machines in the production line. Then, the bottleneck is downstream stage i and thus an arrow is drawn from station i to $i+1$.

If:

$$mb_i < ms_{i+1}: i = 2, \dots, M$$

Then, the bottleneck is upstream of stage $i+1$, and an arrow is drawn from $i+1$ to i. The machine with no departing arrows is identified as the bottleneck.

If there are multiple machines detected as the bottleneck, the machine that is detected as a bottleneck and has the highest *bottleneck severity* is the bottleneck. Bottleneck severity is defined as:

$$S_1 = ms_2 - mb_1,\ S_M = mb_{M-1} - ms_M$$

$$S_i = (mb_{i-1} - ms_{i+1}) - (mb_i - ms_i) : i = 2, \dots, M-1$$

All formulas mentioned above can be found in Li and Meerkov (2009).

3.2.5 Turning point method

The turning point method (TPM) is developed by Li et al. (2007). Just like with the arrow method, TPM uses machine *blockage and starvation times* as a percentage of the total time per machine, respectively TB_i (%) and TS_i (%), for each station i to identify the location of the bottleneck. Blockage time is the percentage of the available time the machine is idle, because it has nothing to produce. This means that it has no order to produce or has reached a sufficient level of stock. Starvation time is the percentage of the available time the machine is idle, because it is waiting for parts from upstream. The TPM method makes two observations:

The first observation is that stations upstream from the bottleneck are blocked and stations downstream from the bottleneck are starved. This results in a positive $TB_i - TS_i$ for its upstream stations and a negative $TB_i - TS_i$ for its downstream stations. This makes the bottleneck station a “turning point”.

The second observation is that a bottleneck station is neither starved nor blocked. This means that the total blockage and starvation time of a bottleneck station $(TB_j + TS_j)$ should be smaller than the upstream and downstream stations.

Therefore, machine m_j is the turning point if all of the following equations are satisfied:

$$TB_i - TS_i > 0: i = 1, \dots, j-1, j \neq 1, j \neq M,$$

$$TB_i - TS_i < 0: i = j+1, \dots, M, j \neq 1, j \neq M,$$

$$TB_j + TS_j < TB_{j-1} + TS_{j-1}, \qquad j \neq 1, j \neq M,$$

$$TB_j + TS_j < TB_{j+1} + TS_{j+1}, \qquad j \neq 1, j \neq M,$$

If $j = 1$,

$$TB_1 - TS_1 > 0 \; and \; TB_2 - TS_2 < 0$$

$$and \; TB_1 + TS_1 < TB_2 + TS_2$$

If $j = M$,

$$TB_{M-1} - TS_{M-1} > 0 \; and \; TB_M - TS_M < 0$$

$$and \; TB_M + TS_M < TB_{M-1} + TS_{M-1}$$

See Li et al. (2007) for the details.

If there are multiple machines detected as the bottleneck, the machine that is detected as a bottleneck with the maximum *bottleneck index* is the bottleneck. Where bottleneck index is defined as:

$$I_1 = \frac{TS}{TB_1 + TS_1}, I_M = \frac{TB_{M-1}}{TB_M + TS_M},$$

$$I_i = \frac{TB_{i-1} + TS_{i+1}}{TB_i + TS_i} : i = 2, \dots, M-1$$

For details of the bottleneck index, see Yu and Matta (2014). This method can be used to detect the bottleneck in serial production lines as well as complex serial manufacturing systems.

3.2.6 Active period method

The active period method (Roser, Nakano, & Tanaka, 2002) is based on the duration that a machine is in *active mode*. The active mode includes the time it produces parts, is faulted, has a tool change etc. If the machine becomes idle, the active mode changes into inactive. The momentary (or real-time) bottleneck is the machine with the longest uninterrupted active time. The average active period method defines the bottleneck as the process with the longest average active period. This results in a non-momentary bottleneck. These methods are able to determine the overall effect of the processes on system capacity. This method distinguishes between the time the machine is a sole bottleneck and a shifting bottleneck. It is a flexible method and can be used in a wide variety of systems. A drawback is that it does require extensive process-related data. As a result, this method is only useful if the data is available.

3.2.7 The bottleneck walk

The bottleneck walk (Roser, Lorentzen, & Deuse, 2014) is based on the active period method while avoiding the extensive data requirement. While you walk through the process, you observe the process flow and monitor the data of processes being starved and blocked, and inventory levels. The inventories tend to be full upstream and empty downstream the bottleneck. The state of a process, being starved or blocked, gives more accuracy as a process can never be a bottleneck while it is waiting for another process. If the analysis is made frequently, a shifting bottleneck can be detected. For this method to work, the inventory levels have to be visible at any time. *Visible queueing* means that you have to be able to distinguish the items in stock. Also, visible queueing is only applicable to processes with a single queue for one given resource.

3.2.8 Simulation based

Many real-world systems are too complex (both in terms of size and stochasticity) to be described by analytical functions or equations. Using a simulation model (Lemessi et al., 2012), it is possible to simulate the behavior of such a system. Knowledge about the system and accurate data are vital to build an accurate model. This means that the output of the model can be only as good as the input of the model. The transformation of inputs to outputs makes simulation models interesting as they can provide answers to “What if?” questions. The downsides are that it is very time consuming to make a simulation model and perform a simulation. Also, it is expensive to keep the simulation model up to date with the changes in the production system.

3.2.9 Bottleneck identification method summary

When choosing a method, a trade-off has to be made. We create a table containing their characteristics to be able to compare the methods, see Table 3.1. After researching the current situation in the next chapter, we use this table to filter the methods and choose one or more methods that fit the situation.

***Table 3.1:** Summary of the bottleneck identification methods.*

Method	Data requirement	Results	Bottleneck type	Suitable processes
Process time	Process times	Maximum capacity of the flow line	Historical	Serial production lines with constant cycle times
Utilization	Net production time and effective production time or Active time and total time	The utilization per machine. The machine with the largest utilization is considered to be the bottleneck	Historical	Serial production lines
Average waiting time method	Waiting times	The machines with the longest average waiting times and thus a ranking of the most likely bottleneck	Historical	Systems with infinite buffers
Arrow method	Blockage and starvation probabilities	The most likely bottleneck	Historical	Serial production lines
Turning point method	Blockage and starvation probabilities	The most likely bottleneck	Historical	Serial production lines and complex serial manufacturing systems
Active period method	Machine states (active/ not active)	Uninterrupted active time and with that a ranking of the most likely bottleneck	Momentary/ Real-time	Serial production lines and complex manufacturing systems
Average active period method	Machine states (active/ not active)	Average uninterrupted active time and with that a ranking of the most likely bottleneck	Historical	Serial production lines and complex manufacturing systems
Bottleneck walk	Observed inventory levels and process status	Bottleneck(s)	Momentary/ Real-time	Systems with visible queueing
Simulation based	System parameters	Multiple performance measures	Historical or Expected	Complex manufacturing systems

3.3 Inventory control

According to Axsäter (2015), the objective of inventory control is often to balance conflicting goals. One goal is to keep stock levels down to make cash available for other purposes. Another goal is to have a high stock of finished goods to achieve a high service level. Other goals are to get volume discounts by ordering larger batches or similarly prevent setups by long production runs. Overall, *economies of scale* and *uncertainties* are the main two reasons for having stock. Economies of scale is a saving in costs gained by and increased level of production, which means that ordering in batches occurs. Uncertainties occur in supply, demand, lead times in production and transportation. Section 3.3.1 describes the types of uncertainties. There are four questions that managers can use to systematically establish inventory policies (Silver, Pyke, & Thomas, 2016):

1. How important is the item?
2. Can, or should, the stock status be reviewed continuously or periodically?

3. What form should the inventory policy take?
4. What specific cost or service objectives should be set?

Sections 3.3.2 to 3.3.5 address these four questions. In inventory control policies the stock is characterized by the *inventory position* (Axsäter, 2015):

$$Inventory\ position = stock\ on\ hand + outstanding\ orders - backorders$$

Stock on hand is the stock that is physically on the shelf. *Outstanding orders* are orders that have not yet arrived and *backorders* are units that are demanded but not yet delivered. The ordering decisions are based on the inventory position, but the holding and shortage costs depend on the *inventory level* (Axsäter, 2015):

$$Inventory\ level = stock\ on\ hand - backorder$$

3.3.1 Uncertainty categorization

Koh, Saad and Jones (2002) develop a categorization structure to categorize uncertainty into *input* and *process*, and simultaneously to highlight the uncertainty that occurs in the supply and demand chain of the manufacturing process, see Figure 3.1. Input uncertainty occurs at external supply and demand, and process uncertainty occurs at internal supply and demand. Most research is conducted within input uncertainty and especially at external demand, compared with other uncertainties (Koh et al., 2002; Louly et al., 2008).

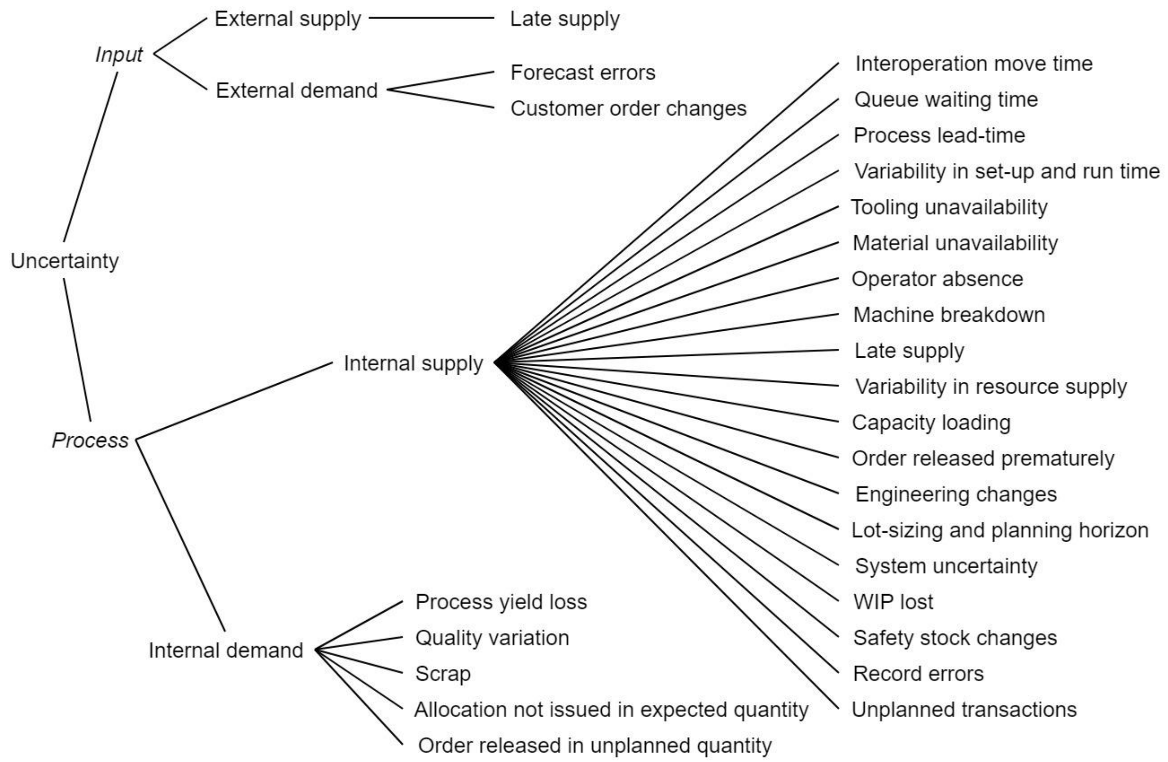


Figure 3.1*: Summary of uncertainties examined by categorization structure* (Koh, Saad, & Jones, 2002).

Buffering against uncertainty can be done by using *safety stock* or *safety lead time*. Safety stock is the amount of inventory kept on hand, on average, to allow for the uncertainty of demand and supply in the short run (Silver et al., 2016). The safety stock levels depend on the desired customer service level. Safety lead time is the difference between the optimal planned lead time and the lead time on average over the planning horizon (Molinder, 1997). Thus, the planned lead time equals the theoretical lead time plus the safety lead time.

Additionally, more accurate forecasting, increased flexibility, and responsiveness are also shown to effectively mitigating the effects of delivery uncertainties (Chung, Talluri, & Kovács, 2018).

Uncertainty at external supply is mainly caused by failure of external suppliers to deliver as ordered. There are multiple opinions on how to deal with this type of uncertainty. Whybark and Williams (1976) suggest that safety stock is more appropriate for buffering quantity uncertainty and safety lead time for dampening timing uncertainty. However, Grasso and Taylor (1984) prefer safety stock for both quantity and lead time uncertainties.

Uncertainties in external demand refer to inaccurate forecasts and customer order changes. This type of uncertainty is extensively researched. To buffer against uncertainty at external demand, usually safety stock is applied. Also, multiple dampening approaches are examined to reduce the uncertainty, such as improving the forecast accuracy (Sridharan & LaForge, 1989; Fildes & Kingsman, 1997) or freezing the master production schedule (Sridharan & LaForge, 1994).

Internal supply uncertainty occurs at the supply chain within the manufacturing cycle of the MRP planned internal manufacture. For example, parts arriving late from the previous workstation due to machine breakdown, operator absence or tooling unavailability. Vargas and Dear (1991) identify that safety stock should be used to buffer both internal supply and external demand uncertainties.

Internal demand uncertainty occurs within the demand chain of the manufacturing cycle of the MRP planned manufacture. An example is variation in quality resulting in part shortages. If the planned scrap factor is lower than the actual scrap level, a yield loss is encountered. This yield loss will be reflected at the output of the related workstation, which is mimicked as internal demand. In other words, there is quantity uncertainty within the output of the workstation. Kurtulus and Pentico (1988) propose the use of safety stock to buffer process yield loss.

3.3.2 Inventory classification

The first step to systematically establish inventory policies is to establish how critical the item under consideration is to the firm. Typically, somewhere on the order of 20% of the SKUs account for 80% of the total annual dollar usage (Silver et al., 2016). This suggests that all SKUs in a firm's inventory should not be controlled to the same extent. It is common to classify inventory by means of an ABC analysis. Class A items should receive the most personalized attention. These are usually the first 5% to 20% of the SKUs with the highest dollar volume. Class B items have an intermediate dollar volume and roughly 30% of the total SKUs fall into this category. The remaining items fall into class C. For these SKUs, the decision system must be kept as simple as possible.

The traditional ABC analysis only includes the value per unit and the sales of the product, together they form the dollar volume. Using only this criterion, the importance of the SKU to the company is not taken into account. Multiple extensions of this analysis are researched and include other criteria such as criticality, sales pattern and commonality (Cohen and Ernst, 1988; Flores and Whybark, 1987).

3.3.3 Continuous versus periodic review

The *review interval (R)* is the time that elapses between two consecutive moments at which the stock level is known. How often the inventory status should be determined specifies the review interval. There are two ways to review inventory: *periodically* or *continuously* (Silver et al., 2016). Continuous review is an extreme case where the stock status is always known. With periodic review the stock status is determined every R time units. Any time the inventory position is reviewed an order can be placed. If an order is placed, it will be delivered after a certain *lead time (L)*. The lead time is the time from the ordering decision until the ordered amount is available on shelf (Axsäter, 2015). A disadvantage of continuous review in comparison with periodic review is the workload on the staff. The replenishment decision can be made at any moment in time, which makes the load less predictable. Usually the staff prefers a rhythmic pattern over a random pattern. With periodic review items can be grouped and all items within a group can be given the same review interval. Another disadvantage of continuous review is that it is more expensive for fast movers. Fast movers have many transactions per unit of time resulting in higher reviewing costs and reviewing errors. However, for slow movers the reviewing costs are low, because updates are only made when a transaction occurs. The advantage of continuous review is that it has less uncertainty to the value of the stock level. The review period (R) is smaller, which means that the period that needs safety protection is smaller (L versus L+R). Thus, less safety stock is required to attain the same customer service level.

3.3.4 Inventory control policies

After categorizing the item(s) and choosing between continuous or periodic review, we can decide on the form of the inventory control policy. The inventory control policy determines when an order should be placed and what quantity should be ordered. Silver et al. (2016) mention four main inventory control policies for single-echelon systems. Additionally, there is another policy that is studied exhaustively (Janssen, Heuts, & de Kok, 1996). Table 3.2 summarizes these inventory control policies. The models below are infinite horizon models. In practice, Vredestein uses a finite planning horizon for their production. We can still use these models, because in practice the decisions that are made only include information from the finite planning horizon. This has three reasons. First, in actual applications a rolling schedule procedure is almost always used, and this is also the case for Vredestein. Specifically, although replenishment quantities may be computed over the entire planning horizon, only the most immediate decisions are implemented (Silver et al., 2016). Second, we look at two types of uncertainties that are short term influences as will be explained in Section 4.4.1. Thus, we do not need to observe the influence of long term changes on safety stock. Third, the lead time plus review period is smaller than the period with advanced demand information. Thus, the safety stock buffers for a period within the planning horizon. This means that the decisions that are made using the infinite model are only including information from the finite planning horizon if a rolling schedule procedure is implemented.

Table 3.2: *Inventory control policies.*

Lot size	Periodic review	Continuous review
Fixed order quantity	(R,s,Q)	(s,Q)
Variable order quantity	(R,S), (R,s,S)	(s,S)

In the table *R*, *s*, *S* and *Q* respectively stand for the review period (or review interval), the reorder point, the order-up-to level and the order quantity.

(s,Q) policy

The (*s,Q*) policy is a continuous-review system. If the inventory position drops to the reorder point *s* or below, a fixed quantity *Q* is ordered. The advantages of this policy are that it is quite simple and the requirements for the supplier are predictable. A downside is that the system cannot cope with individual transactions that are large. A very large transaction can result in a replenishment of size *Q* that does not raise the inventory above the reorder point.

(s,S) policy

The (*s,S*) policy is also a continuous review system. In contrast to the (*s,Q*) policy, the (*s,S*) policy uses a variable replenishment quantity. If the inventory position drops to the reorder point *s*, a variable order quantity is used to raise the inventory position to the order-up-to level *S*. Note that if all demand transactions are unit sized, the (*s,Q*) and (*s,S*) policies are identical because the replenishment requisition will always be made when the inventory position is exactly at *s*, that is, $S = s + Q$ (Silver et al., 2016). A downside of this policy is the computational effort to find the best values for *s* and *S*. This policy can be preferable for class A items as the potential savings are appreciable. A disadvantage of the (*s,S*) policy is the variable order quantity, which has a higher chance for errors and can be inconvenient from a packaging or handling standpoint.

(R,S) policy

The (*R,S*) policy is a periodic review system. Every *R* units of time a variable order quantity is used to raise the inventory position to the order-up-to level *S*. This policy is common in companies without sophisticated computer control. Disadvantages are the varying replenishment quantities and the higher carrying costs in comparison with the continuous-review system. The system is preferred in terms of coordinating the replenishments of related items. Thus, it is frequently used when multiple items are ordered from the same supplier or require resource sharing and the carrying costs can be reduced.

(R,s,S) policy

The (*R,s,S*) policy is a combination of the (*s,S*) and (*R,S*) policy. Every *R* units of time the inventory position is reviewed. If the inventory position is at or below the reorder point *s*, a variable order quantity is used to raise it to the order-up-to level *S*. If the inventory position is above *s*, no order is placed until the next review moment. Note that if $R = 0$ the (*s,S*) and (*R,s,S*) policies are identical and that (*R,S*) is a special case of (*R,s,S*) where $s = S - 1$. It has been shown that the best (*R,s,S*) policy produces a lower total of replenishment, carrying, and shortage costs than any other system (Silver et al., 2016). However, obtaining the best policy (i.e. the three control parameters) is a large computational effort. Thus, this policy is only suitable for A items. Another downside is the variable order quantity (see the (*s,S*) policy).

(R,s,Q) policy

The (*R,s,Q*) policy is a combination of the (*R,s,S*) and (*s,Q*) policies. Every *R* units of time the inventory position is reviewed. If the inventory position is at or below the reorder point *s,* an integral multiple of a fixed quantity *Q* is used, such that the inventory position is raised to a value between s and s + *Q*. If the inventory position is above *s*, no order is placed until the next review moment. Because it is possible to order a multiple of *Q*, this policy is also referred to as the (*R,s,nQ*) policy (Larsen &

Kiesmüller, 2007). In comparison with the (*s,Q*) policy, this policy is able to cope with individual transactions that are large. In comparison with the (*R,s,S*) policy, this policy has a fixed order quantity, which can be convenient from a packaging or handling standpoint.

3.3.5 Cost and service objectives

If the demand or delivery is probabilistic, there is a chance a *stockout* occurs. A stockout is an event that causes inventory to be exhausted. Inventory is kept to limit the number of stockouts, but at the same time excess inventory is undesirable. There are four possible methods to balance these two types of risks. The choice among the four methods should be in line with the customer's perceptions of what is important. The four possible methods that define the safety stock are (Silver et al., 2016):

- *A simple-minded approach*. A common safety factor or a common time supply is assigned as the safety stock of each item.
- *Minimizing cost*. This approach makes a trade-off between the costs of a shortage and the inventory holding costs. The cost-minimizing approach finds the lowest cost policy.
- *Customer service*. The service level becomes a constraint in establishing the safety stock of an item. This approach is often used if the costs of a shortage are difficult to define.
- *Aggregate considerations*. Instead of focusing on the service level of a single item, this approach aims at a desired aggregate service level across a group of items. Given a budget, the safety stocks of individual items are defined to provide the best aggregate service level.

In Section 4.4.1, we decide that customer service is the method that is in line with the customer's perception. The customer service is connected to the safety stock. The safety stock can be calculated with Equation 3-1. This equation takes both demand and supply uncertainty into account.

***Equation 3-1**: Safety Stock (Silver et al., 2016).*

$$\boldsymbol{Safety\ stock\ (SS)} = k * \sigma_{L+R}$$

$$With{:}\ \sigma_{L+R} = \sqrt{(L+R) * \sigma_D^2 + D^2 * \sigma_L^2}$$

k: $Safety\ factor$
σ_{L+R}: $Standard\ deviation\ of\ demand\ during\ the\ lead\ time\ and\ review\ period$
L: $Lead\ time$
R: $Review\ period$
D: $The\ demand\ in\ meters\ per\ shift$
σ_D: $Standard\ deviation\ of\ demand$
σ_L: $Standard\ deviation\ of\ the\ lead\ time$

Safety factor *k* is determined by the desired level of customer service. There are three common measures of service:

The *cycle service level*, P_1, is a specified probability of no stockout per replenishment cycle. Thus, P_1 is the fraction of cycles in which a stockout does not occur.

Equation 3-2*: Cycle service level.*

$$\boldsymbol{Cycle\ service\ level\ (CSL)} = P(X_{L+R} \leq \mu_{L+R} + SS)$$

$$And: \quad k = \Phi^{-1}(P_1)$$

X_{L+R}: Demand during the lead time and review period
μ_{L+R}: Mean demand during the lead time and review period
SS: Safety stock
k: Safety factor
P_1: Probability of no stockout per replenishment cycle
Φ: Standard Normal distribution function

The *fill rate*, *P*$_2$, is a specified fraction of demand to be satisfied routinely from available inventory. Thus, the fill rate is the fraction of demand that is met without backorders or lost sales.

Equation 3-3*: Fill rate.*

$$\boldsymbol{Fill\ rate} = 1 - \frac{ESPRC}{D}$$

$$With: \quad ESPRC = \sigma_{L+R} * G(k)$$

$$And: \quad G(k) = \varphi(k) - k[1 - \Phi(k)]$$

$ESPRC$: Expected shortage per replenishment cycle
D: Expected demand in a replenishment cycle
σ_{L+R}: Standard deviation of demand during the lead time and review period
k: Safety factor
φ: Standard Normal density function
Φ: Standard Normal distribution function

The *ready rate*, *P*$_3$, is the fraction of time during which the net stock is positive. Thus, the fraction of time that there is some stock on the shelf.

Equation 3-4*: Ready rate.*

$$\boldsymbol{Ready\ rate} = \frac{\sigma_{L+R}}{D}\left[G(k) - G\left(k + \frac{D}{\sigma_{L+R}}\right)\right]$$

$$With: \quad G(k) = \varphi(k) - k[1 - \Phi(k)]$$

D: Total demand in the replenishment cycle
σ_{L+R}: Standard deviation of demand during the lead time and review period
k: Safety factor
φ: Standard Normal density function
Φ: Standard Normal distribution function

3.3.5 Perishable goods

Perishability refers to the physical deterioration of units of a product (Silver et al., 2016). The inventory control policies described in Section 3.3.4 do not take a limited lifetime into account. However, the characteristics of rubber change over time and at some point in time, the rubber becomes unusable. Rubber that exceeds its lifetime becomes waste, also called obsolete. Thus, the perishability of the SKU should be taken into account to prevent large losses. There are two types of perishable items, fixed or random, depending on the lifetime of the SKU. For SKUs with a fixed lifetime, the utility is essentially constant during its lifetime and the utility drops notably after its lifetime. For SKUs with a random lifetime, the utility decreases throughout the lifetime. Dealing with perishable goods can result in obsolescence costs. Perishable goods often use a FIFO, first-in-first-out, issuing policy. FIFO is an optimal issuing policy, particularly where the issuing organization has complete control over the issuing actions (Silver et al., 2016). This means that the oldest products in inventory are used first. The storage capacity for wrapping material is limited, see Section 2.7. With the current demand and a shelf life of one month, the storage capacity ensures that items will never perish. Thus, we can use the inventory control policies described in Section 3.3.4, if we take the storage capacity into account when determining order quantity *Q* or order-up-to level *S*.

3.3.6 Calculation of parameters for an (*R,s,Q*) Policy

In Section 4.4.1 we decide to apply the (*R,s,Q*) Policy. This section gives the formulas to calculate the parameters based on how they are commonly described in literature. Equation 3-5 defines the reorder point. To calculate the reorder point, we use Equation 3-1 to determine the safety stock.

Equation 3-5*: Reorder Point (Silver et al., 2016).*

$$\boldsymbol{Reorder\ Point\ (s)} = \hat{x}_{L+R} + SS$$

$\hat{x}_{L+R}$: $Expected\ demand\ during\ the\ lead\ time\ and\ review\ period, in\ units$
SS: $Safety\ stock$

Inventory control has a direct relation with ordering quantities. The *Economic Order Quantity (EOQ)* was introduced by Harris (1913) to determine the optimal order quantity. Equation 3-6 presents the EOQ formula.

Equation 3-6*: Economic Order Quantity (Silver et al., 2016).*

$$\boldsymbol{Economic\ Order\ Quantity\ (EOQ)} = \sqrt{\frac{2*A*D}{h*v}}$$

A: $Fixed\ costs\ per\ order\ or\ setup$
D: $Annual\ demand$
h: $Annual\ holding\ costs\ charge\ per\ unit$
v: $Unit\ cost\ per\ product$

The method by Nahmias and Olsen (2015) determines the optimal order quantity while taking the storage capacity into account. First, the method checks if the EOQ solution is feasible, i.e. the constraint is not active. The constraint is not active if $\sum_{i=1}^{n} c_i EOQ_i \leq C$, where c_i is the space consumed by one unit of product *i* for *i*=1, 2, .., n and C is the total storage space available. If the constraint is not active, the optimal solution is $Q_i^* = EOQ_i$. If the constraint is active, it means that the constraint is binding. Thus, the solution without the constraint is different from the solution with the constraint. The constraint is active if $\sum_{i=1}^{n} c_i EOQ_i > C$. If the constraint is active, we reduce the order quantities. The first step is to compute the ratios $\frac{c_i}{h_i v_i}$, where h_i is the annual holding costs charge per unit of product *i* for *i*=1, 2, .., n and v_i is the unit costs of product *i* for *i*=1, 2, .., n. If the values are indifferent, we calculate the optimal solution with Equation 3-7.

Equation 3-7: *Optimal order quantity if the ratios are indifferent*

$$\boldsymbol{Q_i^*} = mEOQ_i$$
$$where: m = C/[\textstyle\sum_{i=1}^{n}(c_i EOQ_i)]$$

Q_i^*: $Optimal\ order\ quantity\ of\ SKU\ i$
EOQ_i: $Economic\ Order\ Quantity\ of\ SKU\ i$
C: $Total\ storage\ capacity$
c_i: $Space\ consumed\ by\ one\ unit\ of\ product\ of\ SKU\ i$

If the values are different, we calculate the optimal solution with Equation 3-8. The constant θ, known as the Lagrange multiplier, reduces the lot sizes by increasing the effective holding cost. The value of θ can be interpreted as the marginal benefit of an additional square foot of space. The correct value of θ can be found by trial and error or by a search technique. Note that $\theta > 0$, so that the search can be limited to positive numbers only.

Equation 3-8: *Optimal order quantity if the ratios are different*

$$\boldsymbol{Q_i^*} = \sqrt{\frac{2 * A_i * D_i}{h_i v_i + 2\theta c_i}}$$
$$where: \theta\ is\ a\ constant\ chosen\ so\ that\ \textstyle\sum_{i=1}^{n} c_i Q_i^* = C$$

Q_i^*: $Optimal\ order\ quantity\ of\ SKU\ i$
A_i: $Fixed\ costs\ per\ order\ or\ setup\ for\ SKU\ i$
D_i: $Annual\ demand\ of\ SKU\ i$
h_i: $Annual\ holding\ costs\ charge\ per\ unit\ of\ SKU\ i$
v_i: $Unit\ cost\ per\ product\ of\ SKU\ i$
c_i: $Space\ consumed\ by\ one\ unit\ of\ product\ of\ SKU\ i$
C: $Total\ storage\ capacity$

Finally, with fill rate P2 as service measure (see Section 4.4.1), we use Equation 3-9 to calculate k.

Equation 3-9: *Safety factor k, given P2 as service measure.*

$$\boldsymbol{G(k)} = \frac{Q}{\sigma_{L+R}}(1 - P_2)$$

k: $Safety\ factor$

σ_{L+R}: $\mathit{Standard\ deviation\ of\ demand\ during\ the\ lead\ time\ and\ review\ period}$
Q: $\mathit{Order\ quantity}$
P_2: $\mathit{Fraction\ of\ demand\ satisfied\ directly\ from\ shelf}$

3.3 Conclusion

In this chapter we presented an overview of the necessary theoretical knowledge to tackle our research problems. We focused on the subjects operations management philosophies, bottleneck identification methods, and inventory control.

In Section 3.1 we discussed the most common operations management philosophies to improve the manufacturing performance. The operations management philosophies that are included are total quality management, business process re-engineering, lean manufacturing, theory of constraints, and six sigma. We finished this section with a discussion on the differences between the philosophies.

In Section 3.2 we described several bottleneck identification methods and summarized the methods with a table containing the characteristics of each method. The bottleneck identification methods that are included are the process time method, utilization method, inventory based methods, arrow method, turning point method, active period method, bottleneck walk, and simulation based methods.

In Section 3.3 we discussed various aspects of inventory control. The main two reasons for having stock are economies of scale and uncertainties. We elaborated on the categorization of uncertainty types, the classification of SKUs, and the advantages and disadvantages of periodic and continuous review. We discussed the five inventory control policies described by Silver et al. (2016) and Janssen et al. (1996). These inventory control policies are the (*s,Q*), (*s,S*), (*R,S*), (*R,s,S*), and (*R,s,Q*) policy. Furthermore, we mentioned the different cost and service objectives and provided formulas for the service objectives. Finally, we discussed the influence of perishable goods on inventory control and we provided formulas to calculate the parameters of a (*R,s,Q*) policy.

4. Model framework

This chapter focuses on the model framework. The framework contains steps 1 to 3 of the TOC cycle of ongoing improvement. First, Section 4.1 presents the model framework. Second, we explain the processes within the framework in Sections 4.2 to 4.4. In Section 4.2 we determine the phases for the bottleneck identification process, which form step 1 of the TOC cycle. In Section 4.3 we introduce the phase for the optimization of the bottleneck, which forms step 2 of the TOC cycle. In Section 4.3 we introduce the phases for subordinating the non-bottleneck processes, which form step 3 of the TOC cycle.

4.1 Model framework flowchart

The model framework covers steps 1 to 3 of the TOC cycle of ongoing improvement and consists of seven phases. Phases 1 to 4 form the bottleneck identification method and are described in Section 4.2. Section 4.3 describes Phase 5, which is part of the bottleneck optimization process. Section 4.4 describes Phases 6 and 7 which form the process to align all non-bottleneck processes to support the bottleneck process. Figure 4.1 represents the model framework.

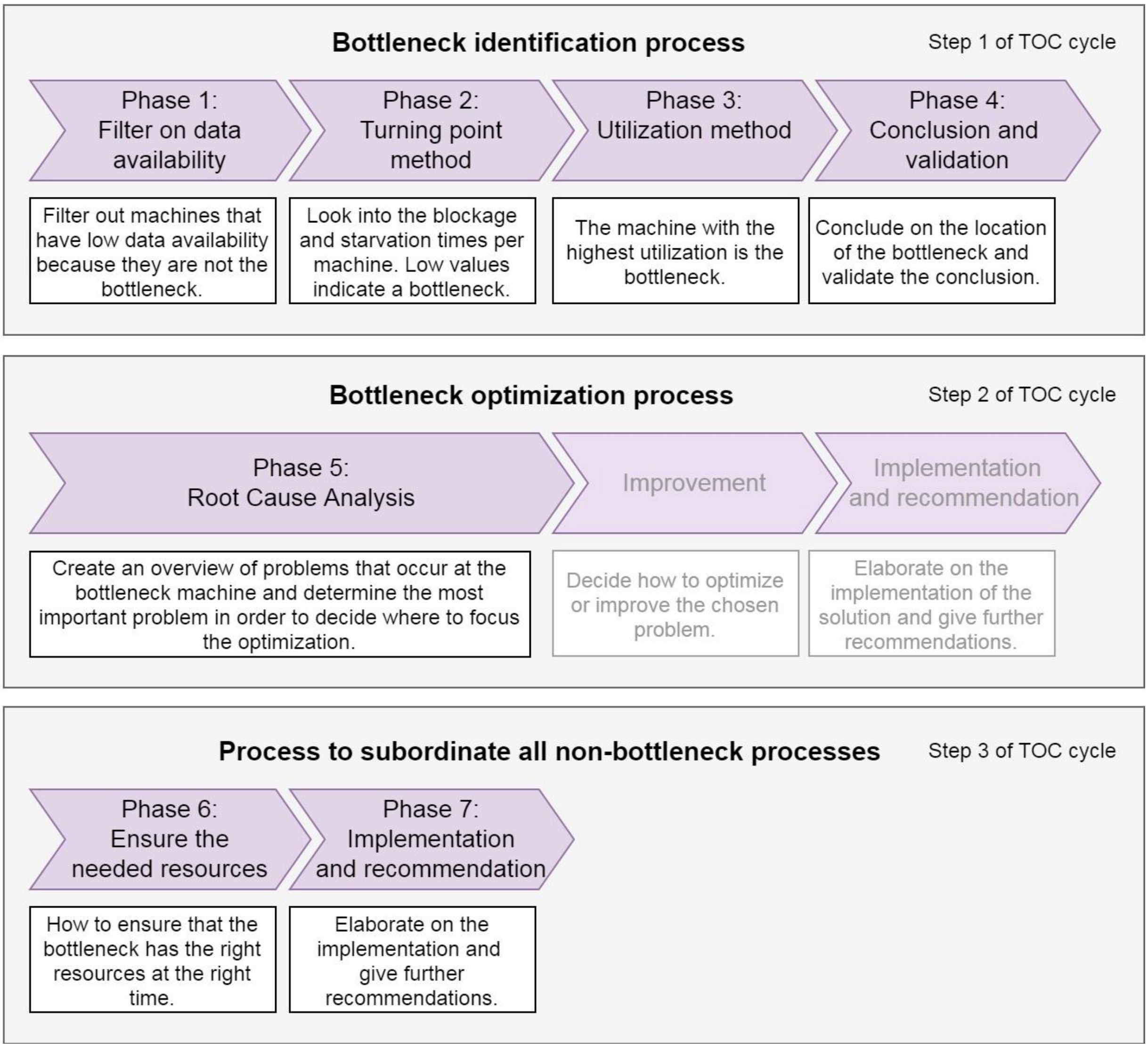


Figure 4.1: *Model framework.*

4.2 Bottleneck identification process

In order to develop a bottleneck identification process, we need to know which identification methods are suitable. First, we discuss the requirements for the bottleneck identification method in Section 4.2.1. In Section 4.2.2 we decide which bottleneck identification method is suitable and in Sections 4.2.3 to 4.2.6 we explain the phases of the bottleneck identification process.

4.2.1 Requirements from Apollo Vredestein

There are some requirements for the bottleneck identification method, because it has to fit the situation at Apollo Vredestein. First of all, the method has to be applicable on complex, parallel systems as the production at Apollo Vredestein is not serial. Second, Apollo Vredestein has finite buffers and does not have visible queueing, see Section 3.2.7. Thus, the method should not require infinite buffers or visibility. Third, Apollo Vredestein has a need to know the historical bottleneck, because they want to know what changes can be made for long term improvements. Monitoring a real-time bottleneck can be used for momentary improvements on the operational level. This is mostly interesting if there is a continuously shifting bottleneck and this is not expected. Also, they ask for a rather simple method that is understandable and workable for Industrial Engineers within Apollo Vredestein. With workable we mean that they have to be able to use the method themselves within a reasonable time frame. Also, they have to be able to alter the method themselves if changes occur. The last requirement is “use what you got”, meaning that the method can only use data if the data is available at Apollo Vredestein.

4.2.2 Suitable bottleneck identification method for Apollo Vredestein

Considering all the requirements, the data availability, and the method characteristics from Table 3.1, none of the bottleneck identification methods satisfy all requirements. We do not use the average waiting time method, active period method and average active period method, because the required data is not available. The bottleneck walk is not applicable, because we are interested in the most significant long-term bottleneck, which is a historical bottleneck. Also, we do not use a simulation based method, because it is not easily altered by others if changes occur, which results in a low workability. We do not use the process time method, because it can only work with constant cycle times (which is not the case) and it only indicates the maximum capacity, not the bottleneck. This results in three remaining methods: the utilization method, arrow method, and turning point method. All these methods are not designed for the system type. This is why we combine the principles of two methods and data availability to identify the bottleneck. We use two methods that are based on (partially) different data, because we want to use the second method as verification. The arrow method and the turning point method base their result on the same data. Thus, we use the arrow method or the turning point method in combination with the utilization method. The turning point method has the advantage that it can also be used on complex serial systems in comparison with the arrow method. Thus, we use the turning point method.

To improve the result of the methods, we use *data availability* to filter out machines with limited data. We define data availability as the amount of available time that is justified in bookings. The data availability varies among the machines. This is caused by different interests from the coordinators. Some machines have a very low utilization, which makes their losses uninteresting for the coordinators. This means that no matter how poor their performance is, they always have enough time to produce what is needed. This results in the operators not being pushed to administrate the losses and therefore almost never administrate the losses. Thus, machines with low data availability never cause problems and therefore are not pushed to be registered correctly. These machines are categorized as non-bottleneck. The data availability rather identifies machines that are not the bottleneck than machines that are a bottleneck.

Thus, we start the identification process by looking at the data availability to prevent using poor data for the two methods. Next, we look at the turning point method, because this method gives a bottleneck as result. Then, we use the utilization method to verify the result. Finally, we form a conclusion indicating the bottleneck and validate the outcome. These four phases cover the first step of the TOC cycle. The bottleneck identification process is designed to support a member of the industrial engineering (IE) department in the process of identifying the bottleneck.

4.2.3 Phase 1: Filtering on data availability

First, we look at data availability. There are many types of data inaccuracy, but we focus on the missing data as explained in the previous section. As we see in Figure 4.2, the net productive time plus the time related to quality, speed, downtime, and scheduled losses should add up to the available time. Therefore, we define missing data by the gap between available time and the sum of net productive time plus all the time related to losses. If this gap is large, it means that many losses are not registered. If the gap is small, it means that a large part of the time is accounted for. Thus, in this case, the data about losses is more accurate. Also, the same reasoning as in Section 4.2.2 applies to machines that have limited or no data: these machines never cause problems at other processes and thus limited data is requested. We conclude that these machines are not the bottleneck and leave them out of succeeding phases. Thus, this phase focuses on machines that we know are not the bottleneck.

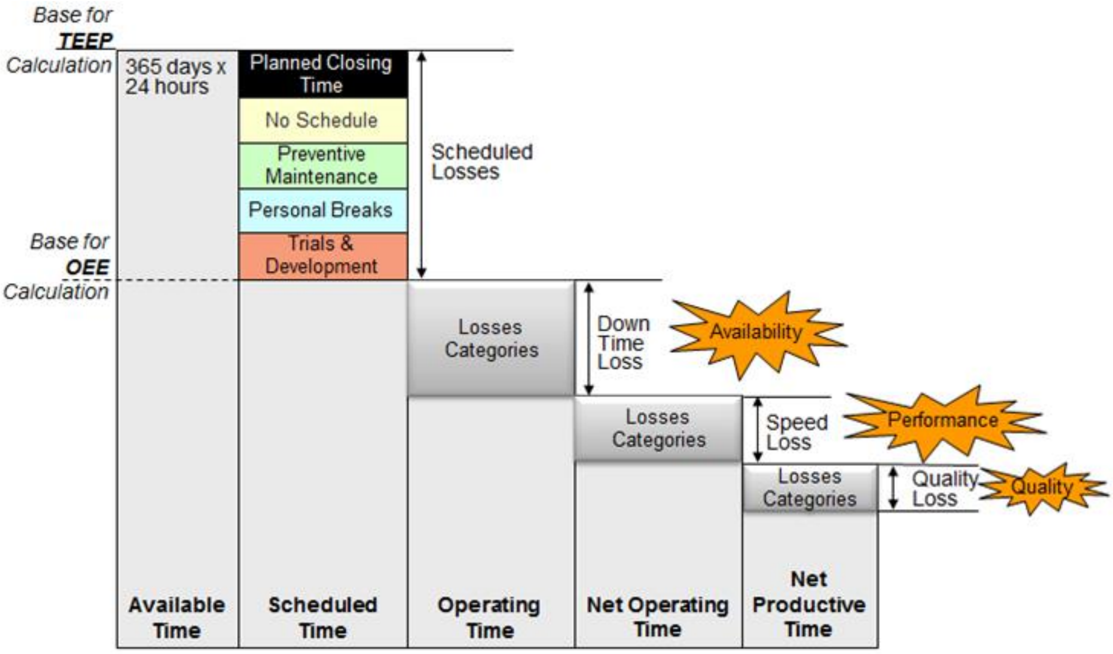


Figure 4.2: *Overview of time definitions with their losses. Reprinted from "Efficiency KPIs v2", by Apollo Vredestein B.V., 2018.*

In practice the gap also includes the category speed loss. All the losses that occur but have no explanation and consequentially are not booked, are included as speed losses. Because they are not booked, they fall into our gap while they should have been categorized as speed losses. The value of the boundary is not an exact value that can be calculated. Because we rather include non-bottleneck machines than exclude bottleneck machines, we rather have the boundary too high than too low. In consultation with a group of employees who have knowledge about the machines and their data, we set the boundary on 50%. This means that if less than 50% of the time is booked, the machine is categorized as non-bottleneck. From here on, the gap between available time and the sum of net productive time plus all the losses is called GAP. The GAP(%) can be calculated using the following formula: $GAP(\%) = \frac{Available\ time - losses - net\ productive\ time}{Available\ time}$.

4.2.4 Phase 2: Turning point method

Next, we use the principle of the turning point method. The "turning point" (j) is the station where the trend changes of blockage being higher than starvation to starvation being higher than blockage. Resulting in $TB_j + TS_j$ (see Section 3.2.5) being the smallest sum in the chain. As we do not have a serial system, it is not clear what causes the starvation or the blockage by looking at TB_i and TS_i. This makes comparing the TB_j with TS_{j+1} not helpful. However, we should still be able to see a rough pattern starting upstream with positive $TB_i - TS_i$, changing into a $TB_i - TS_i$ around zero and ending downstream with a negative $TB_i - TS_i$. Using the principle that $TB_j + TS_j$ is the smallest sum in the chain, both TB_j and TS_j should be close to zero. Thus, the station with the lowest $TB_j + TS_j$ is the bottleneck in a serial system. This method is designed for serial systems, not parallel systems. As a result, it does not take the complexity of a parallel system into account. Thus, we do not want to select the bottleneck immediately. Also, the differences in totals are small for these machines and the lowest sum can also be caused by losses that are not registered. To prevent selecting the wrong machine as the bottleneck, we use a boundary to select the machines to be considered as bottleneck. We cannot calculate an exact value for the boundary, thus we base the boundary on the data. We take a minimum of three machines to be able to compare them. Furthermore, we include machines until the difference with the previous machine is more than 1%, up to a maximum of $TB_i + TS_i = 5\%$. Following these steps, the boundary is set at $TB_i + TS_i < 2\%$, see Table 5.2. This also indicates that if $TB_i + TS_i \geq 2\%$, we categorize the machine as non-bottleneck.

To select a machine as the most significant bottleneck, we compare the amount of starvation caused by the machines. This is different to the first part, where we use the amount of starvation at the machine. Because of the complex system, the first part does not tell us what caused the starvation. Now, we compare the starvation (in minutes) that the machines have caused for subsequent processes only for the machines selected to be considered as a bottleneck ($TB_i + TS_i < 2\%$). We obtain this information by linking the starvation description at a machine, which describes the component that is missing, to the preceding machine where the missing component should be produced, which we obtain from the flowcharts in Appendix 1. We identify the machine that causes the most minutes of starvation for subsequent processes as the bottleneck. Also, we check if the rest of the numbers in this figure match the conclusion from the first part of Phase 2.

4.2.5 Phase 3: Utilization method

Next, we use the utilization method to verify the turning point method (see Section 3.2.2). We define the utilization as the percentage of time a resource is active (Roser et al., 2003). We choose this definition, because it includes the influence of losses such as breakdown and repair time in the calculation. The result is that machines can be identified as the bottleneck if they produce a small part of the time because of high losses.

An *active state* is that state of the machine when the machine produces a part or is being serviced or setup, whereas the *inactive state* of the machine is when the machine is waiting for the part or waiting to be serviced or waiting for the removal of the parts from the machine (Roser et al., 2003). Using the utilization method, the bottleneck is identified by looking at the gap between active time and total time. The smaller the gap, the higher the utilization. The active time includes performance losses and as we mentioned before, performance losses are usually not booked and fall in the GAP. This means that with the data we have, if the performance losses increase, the active time decreases and the utilization decreases, which is not accurate. Thus, we use the inactive time, rather than the active time. The utilization is defined as:

$$Utilization = \frac{Active\ time}{Available\ time} = \frac{Available\ time - Inactive\ time}{Available\ time}$$

Here, the inactive time consists of three inactive states. These are waiting for parts, waiting for service and blocked. The available time is fixed and equals 480 minutes per machine per shift. The machine with the largest utilization is considered to be the most significant bottleneck.

4.2.6 Phase 4: Conclusion and validation

Finally, we conclude on the location of the bottleneck and validate our conclusion. This section elaborates on the conclusion and validation.

Conclusion

We compare the outcomes of the previous phases to determine the location of the bottleneck. Phase 1 only filters and thus does not give an outcome on the location of the bottleneck. If (almost) all machines are filtered out, we should improve the data first. Otherwise, we compare the outcomes of Phases 2 and 3. If Phases 2 and 3 result in the same machine, we conclude that that machine is the bottleneck. If Phases 2 and 3 give a different outcome, we relate this to the principles of the methods. If the machine has a low utilization, but causes a lot of starvation in succeeding processes, it is likely that there is a supporting process limiting this machine. If $1 - utilization$ is higher than the blockage and starvation times, it is likely that the machine is waiting for material handling equipment (MHE) or waiting because of planned breaks for employees that are not substituted. Once we know the origin of the difference, we decide which machine is the most significant bottleneck, or if we should improve both because the capacities are balanced.

Validation

To validate the outcome, we use two additional factors:

1. Knowledge of the daily state of affairs
2. Data reliability

First, we take the knowledge of the daily state of affairs into account. The bottleneck identification process is designed to support a member of the IE department in the process of identifying the bottleneck. A member of the IE department has good understanding of the system and receives a lot of information on weak and strong points within production. This results in available knowledge of the daily state of affairs.

Second, we gain awareness of the data reliability, especially for the two machines in consideration. We think about what we know about wrong bookings that might affect Phases 2 or 3.

We validate our conclusion by comparing the conclusion with the knowledge of the daily state of affairs or by checking the data reliability. If the knowledge of the daily state of affairs matches the outcome of Phases 2 and 3, it is assumed that the data is reliable because the data reflects the problems observed on the work floor. If the outcomes of Phases 2 and 3 do not match the knowledge of the daily state of affairs, it is probable that the data is not reliable. If so, we try to understand how the data is generated and what part of the data is not reliable. Also, we think about possible causes for incomplete knowledge of the daily state of affairs. If Phases 2 and 3 give a different outcome, we consider if there is an explanation considering the data that the outcomes are different. We use that to decide which outcome defines the location of the bottleneck. Also, we think about possible improvements in reliability considering generating data to improve the bottleneck identification process.

4.3 Bottleneck optimization process

The bottleneck optimization process consists of three phases. Phase 5 performs a root cause analysis. Depending on the root cause analysis we go to the improvement phase, and the implementation and recommendation phase. The root cause analysis in Section 5.2 concludes on some options for improvement as a recommendation to the employees within Vredestein. We continue with a loss caused by resources. This is part of the next process in the model framework: the process to subordinate all non-bottleneck processes, see Section 4.4. Thus, in this research we only execute phase 5 of the bottleneck optimization process: the root cause analysis.

Phase 5: Root cause analysis

To structurally solve problems, we identify the root causes of the problem (Heerkens & Van Winden, 2012). First, we formulate the problem as “limited throughput at the bottleneck machine”. To identify potential factors causing limited throughput at the bottleneck machine, we create an Ishikawa diagram with the input of the stakeholders. An Ishikawa diagram, named after its developer Kaoru Ishikawa, is a tool to identify all potential processes and factors that could contribute to a problem (Vorley, 2008). Figure 4.3 shows an example. We use an Ishikawa diagram because this tool is known within Vredestein and because it stimulates to think in all types of potential factors that

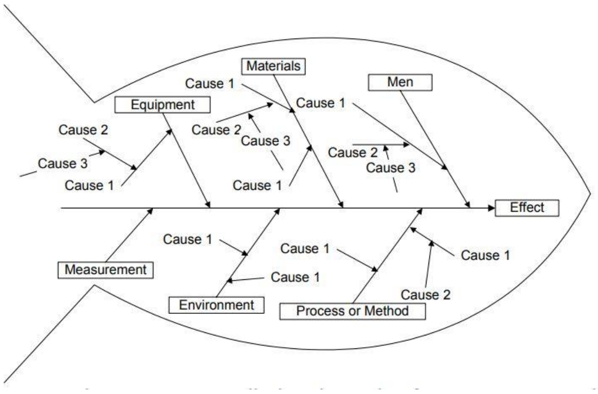


Figure 4.3: *Ishikawa diagram. Reprinted from “Mini guide to root cause analysis”, by Vorley, G., 2018.*

could contribute to the problem. A downside of an Ishikawa diagram is the unclear relationship between causes and problems. Thus, core problems are not directly visible. We reduce the disadvantage of the Ishikawa diagram by adding a separate table that indicates relationships between causes. The problem statement at the head of the diagram is called the effect. This diagram is also known as a fishbone diagram because it looks like the skeleton of a fish, i.e. the head of the fish is the "effect" and the bones represent potential causes. Causes can be applicable on multiple categories and so they can occur more often. The causes emerge by analysis and are grouped into the categories on the main branches of the fishbone. The sub-causes do not necessarily have to fit the classification of the main cause, "Cause 1" (Brook, 2010). We generate the sub-causes by continuously asking why. This is the 5 Why-technique by (Murugaiah, Jebaraj, Srikamaladevi, & Muthaiyah, 2010). This technique stimulates the identification of the root causes.

Next, we prioritize the causes from the previous steps on their risk regarding limited throughput at the bottleneck machine. This helps us to identify the root cause for further research. A risk has two dimensions (Hillson & Hulett, 2004). The first dimension relates to uncertainty and the second dimension relates to what would happen if it occurs. To prioritize the problems, we use a Probability-Impact Matrix (Project Management Institute, 2000). Here, the probability and impact are respectively formulated as frequency of occurrence and loss of time. Combining both assessment criteria results in assessing the total loss. To assist in the assessment, we use one of the four levels of measurement: the ordinal scale (Heerkens & van Winden, 2012). The advantage of an ordinal scale is the ease of comparison between variables without knowing the exact value. We do not need to know the interrelationship between values to be able to rank the causes, which means that the ordinal scale is sufficient. The ordinal scale for both assessment criteria is: Very high - High - Medium - Low - Very Low. To minimize the effect of perceptual bias, we include multiple stakeholders with different backgrounds in the development of the Probability-Impact Matrix. After prioritizing the problems, we decide on which of the problems the focus should be.

4.4 Process to subordinate all non-bottleneck processes

The process to subordinate all non-bottleneck processes to the bottleneck process is step 3 of the TOC cycle (see Section 1.4). This process consists of two phases. These phases are Phases 6 and 7 in the model framework. Phase 6 decides how to ensure that the preceding processes deliver the materials that are needed. Phase 7 discusses the implementation of the solution(s) and further recommendations.

4.4.1 Phase 6: Ensure the needed materials

In this phase we want to know how we can ensure that the bottleneck receives the right materials from preceding processes at the right time. Thus, we decide how to align the non-bottleneck processes to support the bottleneck process. From the root cause analysis in Section 5.2, we concluded to improve the shortage of wrapping material at the ART. In this root cause analysis, we have found two sub-causes to improve. The first sub-cause is "the length of a roll of wrapping material is not measured and not booked". The second sub-cause is "the current buffer for wrapping material is not sufficient". Improving both sub-causes should reduce the shortage of wrapping material.

Length of a roll of wrapping material

We start with the sub-cause "the length of a roll of wrapping material is not measured and not booked", because it influences the amount of stock. Thus, it influences the second sub-cause. It is unclear what the stock level is, because the order quantity is 250 meters but due to scrap losses at previous processes the rolls contain varying amounts of wrapping material. First, we validate the extent of the problem that is the varying length of wrapping material. To do so, we measure the diameter of multiple rolls. We can estimate the length that is on a roll using the surface area. The surface area of the material on a roll is equal to the surface are of the material when the roll is unrolled. I.e. the surface of the circle is equal to the surface of the rectangle. Both surface areas are indicated with the color purple in Figure 4.4 and Figure 4.5. This results in Equation 4-1.

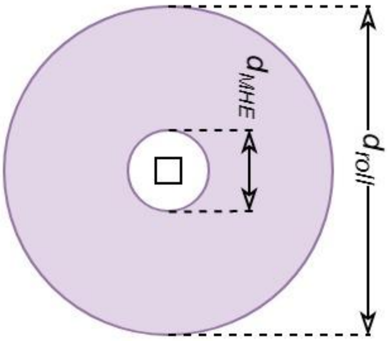


Figure 4.4: *Graphic representation of a side view of a roll of wrapping material.*

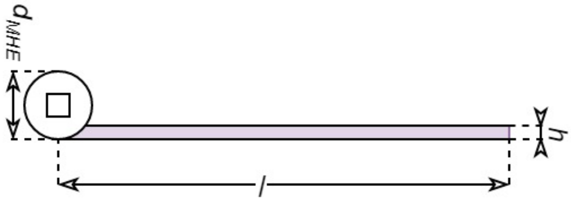


Figure 4.5: *Graphic representation of a side view of an unrolled roll of wrapping materials.*

Equation 4-1*: The length of the material on a roll*

$$\boldsymbol{Length\ of\ material\ (l)} = \frac{\pi\left(\frac{d_{roll}}{2}\right)^2 - \pi\left(\frac{d_{MHE}}{2}\right)^2}{h}$$

$$Because: \pi d_{roll} - \pi d_{MHE} = l * h$$

d_{MHE}: $The\ diameter\ of\ material\ handling\ equipment\ (MHE)$
d_{roll}: $The\ diameter\ of\ the\ roll\ (MHE\ including\ the\ material\ on\ it)$
l: $The\ length\ of\ the\ material\ that\ is\ on\ the\ roll$
h: $The\ height\ (or\ the\ thickness)\ of\ the\ material\ that\ is\ on\ the\ roll$

To verify the estimation, we measure the diameter of one roll and the length of that roll. This verification is limited to one roll, because the roll becomes scrap after measuring. The difference between our estimation and the real length is 1.01 meter, which is 0.7% of the total length. Explanations for the deviation can be the variation in thickness of the material, measurement inaccuracy or variation in how tightly the material is rolled up. A deviation of 0.7% means that the estimation is a good indicator for the length of the roll, but it would be better to assess multiple rolls to see the deviation of the measure among the rolls.

Next, we gather the characteristics of a roll of wrapping material using the measured data and decide whether we should change the current approach.

Inventory control for wrapping material

Next, we continue with the sub-cause "the current buffer for wrapping material is not sufficient". We deal with fluctuations or uncertainties, and the current buffer is not sufficient enough to compensate this, resulting in a shortage of material. To reduce the shortage of material, we set up a new inventory control policy. The purpose of inventory control policies is to determine when and how much to order, as well as how to maintain appropriate stock levels to avoid shortages. In this case, the reason for having stock is uncertainties. We deal with both types of process uncertainty: internal supply and internal demand uncertainty (see Section 3.3.1). The biggest influence on internal supply uncertainty is queue waiting time and on internal demand uncertainty is scrap. We take these two types of uncertainty into account to determine appropriate stock levels. The varying length of a roll of wrapping material and the number of rolls that are cut from half a calendar roll are uncertainties caused by scrap. Scrap is a quantity uncertainty and queue waiting time a timing uncertainty. There are opposite opinions in literature on how to include quantity and timing uncertainty, see Section 3.3.1. We decide to use safety stock for both types of uncertainty, because the safety lead time is used as a general measure within the company (see Section 2.7). To keep a clear distinction between machine specific and general buffers, we use safety stock for uncertainty caused by scrap and queue waiting time. This new inventory control policy will consist of the original safety lead time of two hours and a yet to be defined safety stock. In the current situation the safety lead time of two hours buffers for all uncertainties and this is not sufficient. The proposed policy includes a safety stock for queue waiting time and scrap uncertainty and a two-hour safety lead time for the other remaining uncertainties that occur. This means that the safety stock and performance regarding the queue waiting time and scrap uncertainty do not take the safety lead time and other uncertainties into account.

To set up inventory control for wrapping material we answer the four questions to systematically establish inventory policies (Silver, Pyke, & Thomas, 2016):

1. How important is the item?
2. Can, or should, the stock status be reviewed continuously or periodically?
3. What form should the inventory policy take?
4. What specific cost or service objectives should be set?

First, we decide on the importance of an item. We look at a small part of the entire system and define an inventory control policy for two SKUs. The common classification methods, mentioned in Section 3.3.2, rank the SKUs based on some criteria. In this case, a ranking does not give the desired results because we only have two SKUs. Using a ranking we can state that one SKU is more important than the other, but we cannot state that both are important or unimportant. Because of this, we do not make a classification based on a ranking, such as the percentage of total annual dollar usage. Both SKUs are input material for the bottleneck and, as we recall from Section 1.4, the throughput of the system is determined by the throughput of the bottleneck. Thus, a stockout at the bottleneck is a loss of the entire system. This means both SKUs have a high criticality and we therefore classify them as A items (see Section 3.3.2).

Second, we choose between a continuous or periodic review period. Vredestein updates their planning after every shift of 8 hours. Within these 8 hours, the demand does not change. The semi-finished products needed to build the greentyres must be present two hours before the order starts at the building machine. Thus, revising the planning of the building department does directly influence the planning of the semi-finished products. Because the current production planning is based on a periodic review, we choose to also periodically review the stock level. To minimize the uncertainty of the stock level we choose a periodic review with review period *R* equal to one shift of 8 hours. Thus, the demand is set per 8 hours and the stock is reviewed every 8 hours. The advantage is a lower safety stock compared to a longer review period. This is desired because the space for the stock of wrapping material is limited. Also, we are dealing with perishable goods. The wrapping material has a shelf life up to one month. If the material is older than one month, it has to be disposed of. This is another reason to strive for low safety stocks.

Third, we choose an inventory control policy. The wrapping material has a fixed order quantity (see Section 2.7). From Table 3.2 in Section 3.3.4 we see that the (*R,s,Q*) policy is a periodic review policy and uses a fixed order quantity *Q*. The advantage of the (*R,s,Q*) policy is that we can order a multiple of *Q*. This means that the policy is able to raise the inventory above the reorder point *s* if individual transactions are large. The storage capacity for wrapping material is limited, which ensures that items will never perish. Thus, we can use the (*R,s,Q*) policy if we use the method described by Nahmias and Olsen (2015) to take the storage capacity into account when determining order quantity *Q*.

Fourth and last, we decide on the cost or service objective. The goal is to serve the customer, the ART. It is the bottleneck machine and therefore a high service level is required. Thus, we choose the method “customer service” to define the safety stock. Another option is the minimizing cost method. The shortage costs of a bottleneck machine are high, which also results in a high desired service level. Nevertheless, we choose the customer service method, because the shortage costs are difficult to define. We can calculate the costs related to the production of a tyre that is asked but not made, but we do not know the intangible costs, such as reputation damage. The service level is determined by the company, based on their vision of what is acceptable or desired. Within the customer service method, there are three common measures: cycle service level, fill rate and ready rate (see Section 3.3.5). Because the time of the bottleneck machine is valuable, the amount of shortage and not the number of stockout occasions has a large influence on the shortage costs. Every minute that is lost on the bottleneck machine, could have been used to produce more beads and fulfil a part of the demand. This means that the longer the stockout, the larger the fraction of demand that is not satisfied. Thus, we use the fill rate as service measure because the duration of a stockout is taken into account.

Performance of inventory control

We measure the performance of inventory control by the fill rate, the expected shortage, the average stock level and the cost of inventory. We calculate the fill rate with and derive the expected shortage from Equation 3-3. We calculate the cost of inventory using Equation 4-2 and derive the average stock level from Equation 4-2. The cost of inventory includes ordering cost and holding or carrying cost. We do not include obsolescence cost, because the storage capacity ensures items will never perish.

***Equation 4-2**: Cost of inventory.*

$$\boldsymbol{TC} = \frac{AD}{Q} + hv\left(\frac{Q}{2} + SS\right)$$

A: Fixed costs per order or setup
D: Annual demand
Q: Ordering quantity
h: Annual holding costs charge per unit
v: Unit cost of SKU
SS: Safety stock

4.4.2 Phase 7: Implementation and recommendations

Finally, in Phase 7 we discuss the recommendations for implementation. We give an overview of the options that we recommend to implement and cover how these can be implemented. We execute this phase in Section 5.5.3.

4.5 Conclusion

In this chapter we set up the model framework. The model framework includes seven phases that cover steps 1 to 3 of the TOC cycle of ongoing improvement.

In Section 4.1 we presented a flowchart of the model framework. The flowchart contains short descriptions of each phase and groups the phases per step of the TOC cycle.

In Section 4.2 we discussed the bottleneck identification process, which is step 1 of the TOC cycle. We took the requirements of Apollo Vredestein and the characteristics of the bottleneck identification methods (from Section 3.2) into account to set up the bottleneck identification process. The bottleneck identification process consists of four phases. The first phase filters on data availability to identify non-bottlenecks. The second phase performs the turning point method, and the third phase performs the utilization method to identify the bottleneck. Finally, the fourth phase entails a conclusion on the location of the bottleneck and validates the result.

Section 4.3 covered the bottleneck optimization process (step 2), which consists of Phase 5: root cause analysis. The root cause analysis includes an Ishikawa diagram and a Probability-Impact Matrix to determine a focus of improvement.

Section 4.4 described the process to subordinate all non-bottleneck processes (step 3). Phase 6 includes steps to ensure that the bottleneck receives the right materials from preceding processes at the right time. First, we described a method to estimate the length of a roll of wrapping material to increase the accuracy of the inventory. Second, we decided on the inventory control policy. Third, we described how to measure the performance of the inventory control policy. Phase 7 discusses how the solution(s) for alignment can be implemented. This will be executed in Chapter 5.

5. Model implementation

In this chapter we execute the phases of the model framework. First, in Section 5.1 we go through Phases 1 to 4 of the bottleneck identification process. Second, in Section 5.2 we execute Phase 5 of the bottleneck optimization process. Third, in Section 5.3 we execute the Phases 6 and 7 of the process to subordinate all non-bottleneck processes.

5.1 Bottleneck identification

In this section we execute the four phases of the bottleneck identification process. All the data that we use for the identification of the bottleneck is from the period 14/1/2019-31/3/2019. The period length is based on the most recent data available at the start of the phase while excluding the Christmas holiday during which there is no regular production.

To visualize the principles and provide the information that is needed to perform the phases, we build a dashboard in Power BI. Power BI is a business analytics solution that visualizes the data and shares insights across the corresponding organization. We choose to use Power BI because this has recently been purchased by Apollo Vredestein and is seen as the future of sharing data information for their organization. The dashboard shows the information for the phases and also some of the outcomes. Further information about the dashboard can be found in Appendix 2. Below, we elaborate on the execution of Phases 1 to 4 using the dashboard.

We start with Phase 1: filtering on data availability. Table 5.1 presents the machines with their GAP(%). All machines with a GAP larger than 50% are not the bottleneck, see Section 4.2.3. From the table we conclude that FSW4, HLNLB, 96, 97, 98, 99, 27, and 29 are not the bottleneck. For KAL3 there is missing data on the net productive time, which results in the large GAP. The net productive time is data generated by the system and does not need to be booked. This means that the data is missing due to a program error. Thus, KAL3 is an exception and is included in the next phases. Also, there are four machines: Pugno, HVS2, Calemard, and Paint Cabine that have no data and as a result are not present in the table. Here, we apply the same reasoning as in Section 4.2.2: these machines rarely cause problems at other processes and therefore no data is requested. Thus, we conclude that these four machines are also not the bottleneck. In total, Phase 1 leads to the conclusion that FSW4, HLNLB, 96, 97, 98, 99, Pugno, HVS2, Calemard, and Paint Cabine are not the bottleneck. The remaining machines are identified as possible bottlenecks.

Table 5.1: *GAP (%) per machine.*

Machine	GAP (%)
FSW4	94.08%
HLNLB	85.68%
97	77.12%
29	75.78%
98	73.90%
KAL3	73.79%
99	72.94%
96	67.23%
27	53.34%
BIAS5	41.84%
BIAS7	35.35%
PASM1	35.08%
ORION	25.40%
ART	18.55%
TRIPL	14.56%
KAL4	13.98%
M4	13.75%
M5	13.02%
11	12.85%
M6	11.42%
TINCH	11.25%
43	11.24%
41	10.09%
45	10.09%
9	9.57%
49	9.47%
47	9.45%
Agri Press	9.30%
LTM	7.97%
7	7.78%
55	7.57%
M8	7.11%
53	6.50%
51	0.29%

Next, we continue with Phase 2: the turning point method. To visualize this principle we build a page in the dashboard in Power BI. Figure 5.1 shows the page of the dashboard with the blockage times (TB), starvation times (TS) and TB-TS per station. The dashboard can be filtered on the preferred dates in the left upper corner. In this case, the figure shows the data for the period 14/1/2019-31/3/2019. In the bottom left corner, we see TB and TS per machine in case the process step contains multiple machines, for instance mixing masterbatch (M6&M8). Two exceptions are Agri Press and LTM, because the data is only available for the group of presses and not per press. The machines that are previously categorized by their GAP (%) as non-bottleneck are marked with a red background. If there is no data available, the machine is represented without TB and TS as in the previous flow charts, but also with a red background. We see from the figure that the mixing department has very high TB-TS times and comparable TB and TS per station. Within the semi-finished products department the numbers vary greatly per station from high, to low, to slightly negative TB-TS times. The assembly department has high $TB_i + TS_i$, but the division can differ per station. This leads to positive and negative $TB_i - TS_i$, which is both possible, because at these stations multiple flows are combined for input. Finally, the curing department has high TS and low TB, which we expect because they plan on curing. Table 5.2 shows $TB_i + TS_i$ per machine. From the table we conclude that there are four machines that qualify for the boundary of $TB_i + TS_i < 2\%$: ART, BIAS5, BIAS7, and ORION.

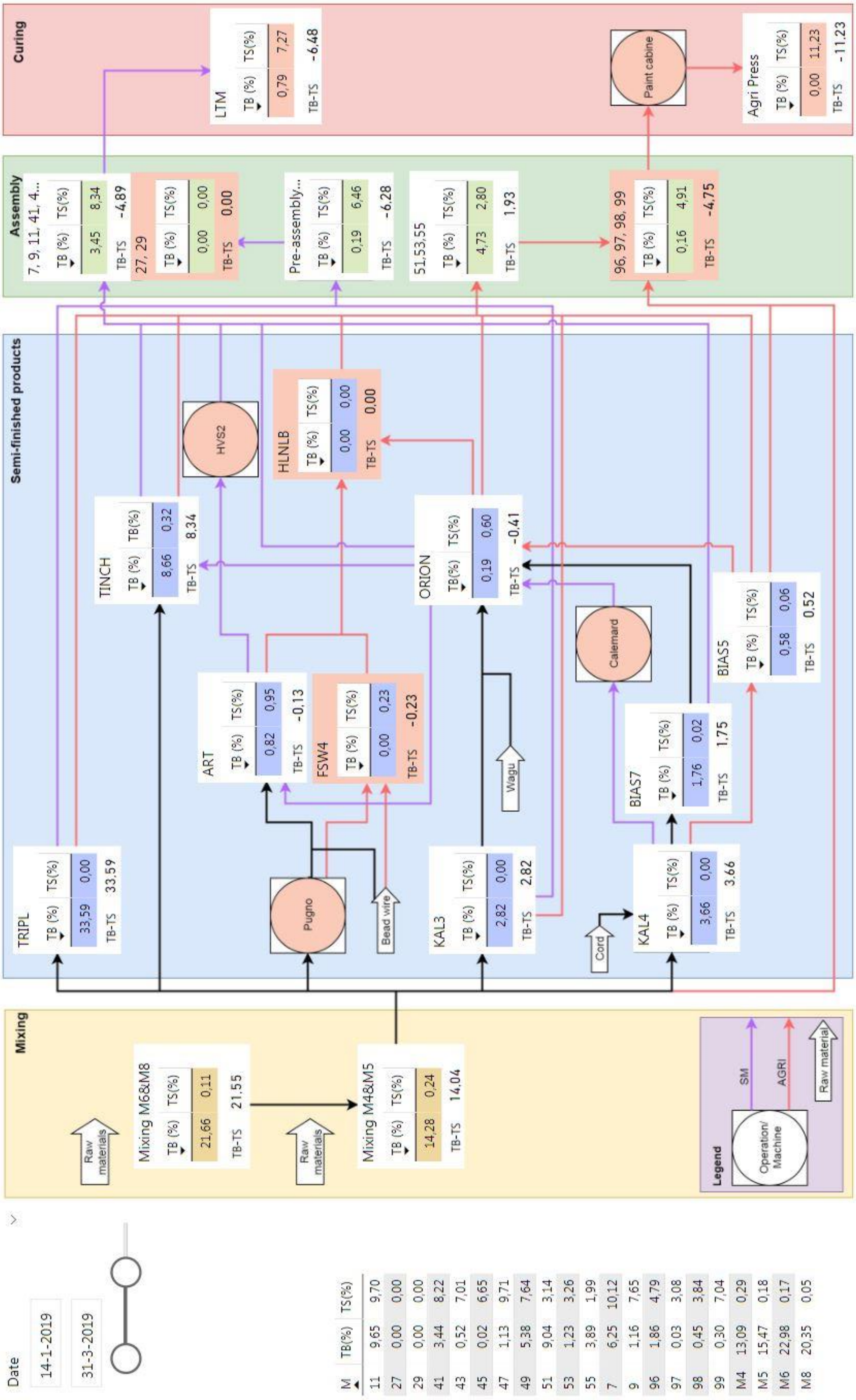
Table 5.2: *$TB_i + TS_i$ (%) per machine.*

Machine	TB+TS (%)		
BIAS5	0.64%	TINCH	8.97%
ORION	0.80%	47	10.84%
ART	1.77%	Agri Press	11.23%
BIAS7	1.78	41	11.66
KAL3	2.82%	51	12.19%
KAL4	3.66%	49	13.02%
53	4.50%	M4	13.37%
55	5.88%	M5	15.65%
PASM1	6.65%	7	16.37%
45	6.66%	11	19.35%
43	7.53%	M8	20.40%
LTM	8.05%	M6	23.15%
9	8.82%	TRIPL	33.59%

Table 5.3: *Utilization (%) per machine.*

Machine	Utilization		
ART	98.00%	M4	86.63%
ORION	97.84%	51	84.77%
KAL3	96.63%	M5	84.35%
KAL4	96.16%	47	84.05%
53	95.16%	9	83.68%
55	93.58%	41	82.20%
BIAS7	92.85%	49	81.12%
LTM	91.95%	TINCH	80.04%
BIAS5	91.07%	M8	79.60%
PASM1	89.36%	7	77.71%
Agri Press	88.77%	M6	76.85%
45	88.39%	11	75.08%
43	86.98%	TRIPL	66.38%

The second part of Phase 2 is represented in Figure 5.2. Here, we see the minutes of starvation caused by the machine (instead of the starvation at the machine). We obtain this information by linking the starvation description at a machine, which describes the component that is missing, to the preceding machine where the missing component should be produced. Again, the dashboard can be filtered on the preferred dates in the left upper corner. In this case, the figure shows the data for the period 14/1/2019-31/3/2019. There is one set of starvation minutes displayed on the left. These are minutes of starvation at the ORION, where the cause of the starvation is not booked. This means that we cannot allocate the starvation to one of the preceding processes. Comparing the starvation caused by the previously selected four machines in Figure 5.2, the ART causes the most starvation. This means that the ART is the most significant bottleneck. Also, when looking at the figure we see that the machines in the assembly department cause large losses at the curing department. The



Date

14-1-2019

31-3-2019

M	TB(%)	TS(%)
11	9,65	9,70
27	0,00	0,00
29	0,00	0,00
41	3,44	8,22
43	0,52	7,01
45	0,02	6,65
47	1,13	9,71
49	5,38	7,64
51	9,04	3,14
53	1,23	3,26
55	3,89	1,99
7	6,25	10,12
9	1,16	7,65
96	1,86	4,79
97	0,03	3,08
98	0,45	3,84
99	0,30	7,04
M4	13,09	0,29
M5	15,47	0,18
M6	22,98	0,17
M8	20,35	0,05

***Figure 5.1:** Dashboard page 2 "Visualization Phase 2"- Visualization of the turning point method.*

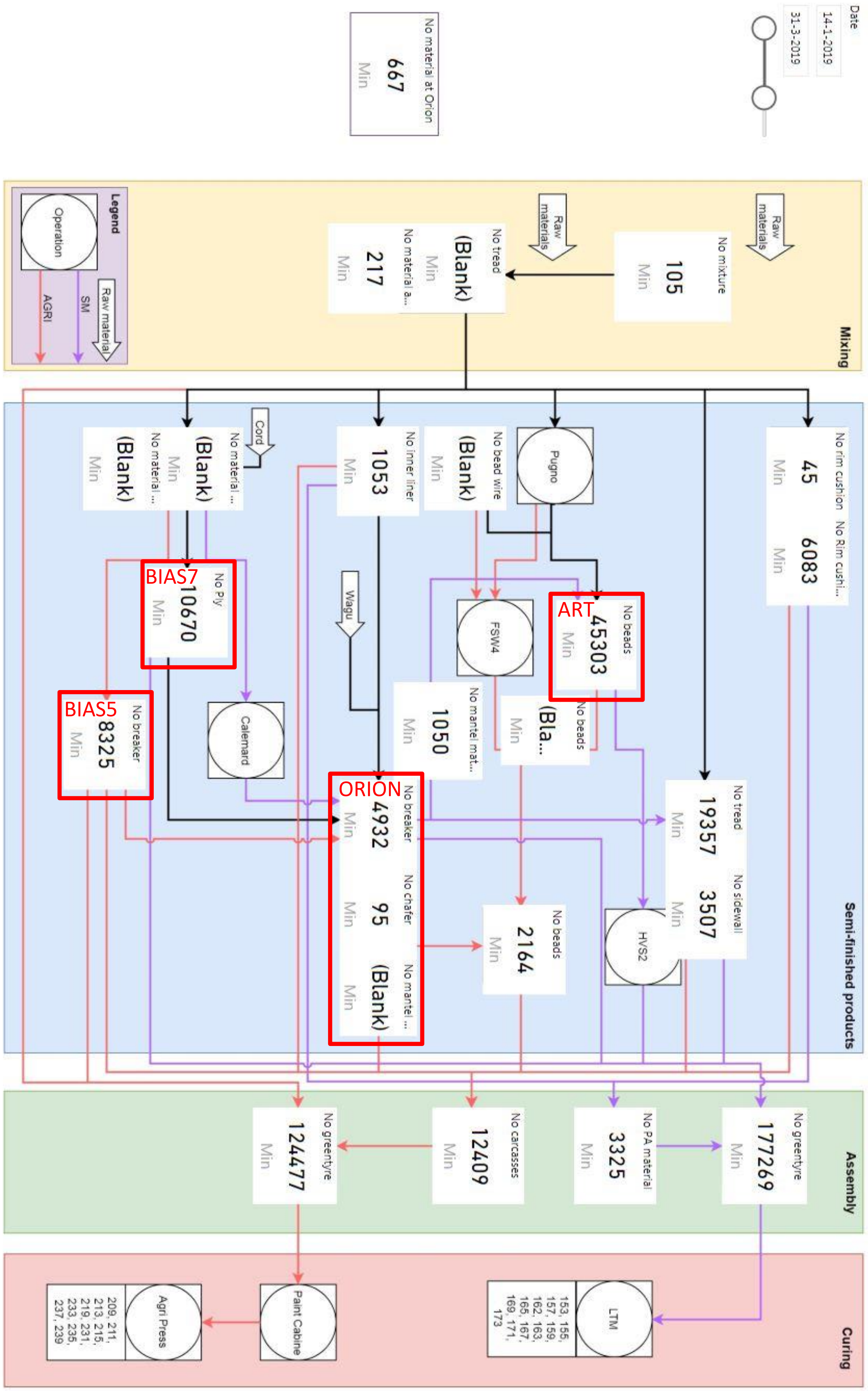


Figure 5.2: *Dashboard page 3 "Caused starvation Phase 2" - Starvation caused by the machines .*

largest loss in the assembly department is caused by no beads at the spot of the ART. The starvation at the ART caused by delivering machines only covers a small part of these losses. This also indicates that the ART is the most significant bottleneck. Another interesting finding is the starvation at the assembly department caused by no tread at the spot of the TINCH. This is the second largest loss in the assembly department, but this machine has plenty of spare time. This research is limited to managing one bottleneck, thus looking at the TINCH is a recommendation for further research.

Next is Phase 3: utilization method. The utilization method results in Table 5.3. From Table 5.3 we see that the ART has the highest utilization. This means that the ART is also the most significant bottleneck when using the utilization method.

The final phase is Phase 4: conclusion and validation. Phases 2 and 3 both indicate that the ART is the bottleneck. Thus, we conclude that the ART is the bottleneck machine. To validate the outcome, we discussed the result with the member of the IE department that is responsible for the part of production that is exclusively for AGRI and SM, and he agreed with it. Because both phases and the knowledge of the daily state of affairs correspond, we expect the data to be reliable and do not further investigate the data reliability. Thus, the validation supports the conclusion that the ART is the most significant bottleneck.

Furthermore, we see from the data that other machines also affect the flow and can be categorized as secondary bottlenecks. These machines are a recommendation for further research. Below, we shortly mention our initial findings for those machines. The ORION is a highly utilized machine causing a small amount of starvation. Because of the high utilization, it is important to keep some focus on this machine to prevent higher amounts of starvation (at the building department). The different order between Table 5.2 and Table 5.3 is caused by the inactive state: waiting for service. The turning point method only takes waiting for service as a consequence of a preceding or succeeding processes into account, which means blockage and starvation times. However, the utilization method also considers waiting for service as a consequence of a lack of material handling equipment or planned breaks for employees that are not substituted. For instance, in Table 5.3 BIAS5 and BIAS7 went down in ranking compared to Table 5.2, which means that the time those machines wait for service that is not caused by a preceding or succeeding process is high. I.e. there is either a lack of material handling equipment or there are planned breaks for employees that are not substituted. Because they cause a lot of starvation, see Figure 5.2, this is also an opportunity for improvement. Furthermore, an interesting finding, as mentioned in the second part of Phase 2, is the starvation at the assembly department caused by “no tread” at the spot of the TINCH. This machine has plenty of spare time, thus a supporting process is causing the starvation. Determining the cause can create understanding for improving the flow. We recommend Apollo Vredestein to further research the findings mentioned above and continue to identify the bottleneck in the future. The identification of the bottleneck can be done once a month or once every few months. It is important to stay updated on the location of the bottleneck to improve the performance at the right place.

5.2 Bottleneck optimization

In this section we execute Phase 5 of the bottleneck optimization process: Root Cause Analysis. In Section 4.3.1, we formulated the problem as “limited throughput at the bottleneck machine”. The ART is identified as the bottleneck, which means that the problem “limited throughput at the bottleneck machine” is equivalent to “limited throughput at the ART”. To create an overview of potential causes, we use ideas of stakeholders. We generate these ideas by brainstorming the potential causes of the problem with the stakeholders. The operators, coordinators, process technologist and industrial engineer of Apollo Vredestein concerned with the ART are the most relevant stakeholders involved. We create an Ishikawa diagram with their input to identify potential factors causing limited throughput at the ART, see Figure 5.3. We use the "4M and 1E" technique (O'Donohue & Maragakis, 2016) to set up the Ishikawa diagram. The "4M and 1E" technique splits the Ishikawa diagram in five categories that form the bones of the diagram. These categories are:

- Man: Anyone involved with the process
- Materials: Raw materials that are used to produce the final product
- Method: How the process is performed and the specific requirements for doing it
- Machine: Any equipment that is required to accomplish the job
- Environment: The conditions in which the process operates

To generate relevant input, we ask questions relating to the five major categories. The main causes are grouped into the categories on the main branches of the fishbone. We generate the sub-causes by continuously asking why. This means that the sub-cause does not necessarily has to fit the categorization of the main cause. Table 5.4 gives an overview of the potential causes and their problem statement. See Appendix 3 for extensive descriptions of the causes. Also, Table 5.5 gives an overview of relationships between causes to minimize the disadvantage of an Ishikawa diagram: the unclear relationship between causes and problems. The table shows which sub-cause influences multiple causes to create awareness.

Next, we identify the root cause. We use a Probability-Impact matrix (Project Management Institute, 2000) to prioritize the previously generated causes based on their frequency of occurrence and loss of time (minutes). We generate the matrix in cooperation with many experienced stakeholders to minimize the effect of perceptual bias. First, we generate information through independently filled out forms (see Appendix 4A). We use anonymous forms to stimulate honest and personal answers. This form is filled out by 10 operators and coordinators and includes employees from each shift. Next, we discuss the average (see Appendix 4B) and individual results with the industrial engineer, process technologist, and one operator concerned with the ART to conclude one final outcome. They agreed to discuss their answers openly. We do not include the individual results from the employees joining the discussion in the average result, because their opinion is already taken into account through the discussion. The discussion is an important part of the process, because they have to convince each other of the importance of the cause. Together, we establish the Probability-Impact matrix in Figure 5.4. The colors in the figure show the rating of the causes. The rating indicates the cause's importance and priority for attention. Red indicates a very important cause that has a high priority and green indicates a cause with very low importance that has a low priority. Thus, the rating consists of five categories: very low – low – average – high – very high. These are respectively represented by the colors: green – light green – yellow – orange – red.

From Figure 5.4 we conclude that the causes in the red area, causes 5, 7, 8, 10, 11, 12, 16 and 17, are important to further analyze. These are respectively having a non-automatic machine, different levels of skill of operators, big defects at the engine, fine-tuning of the machine, manually removing beads, uneven rubberization of steel wires, variation in rubber adhesion to the steel wire, and no

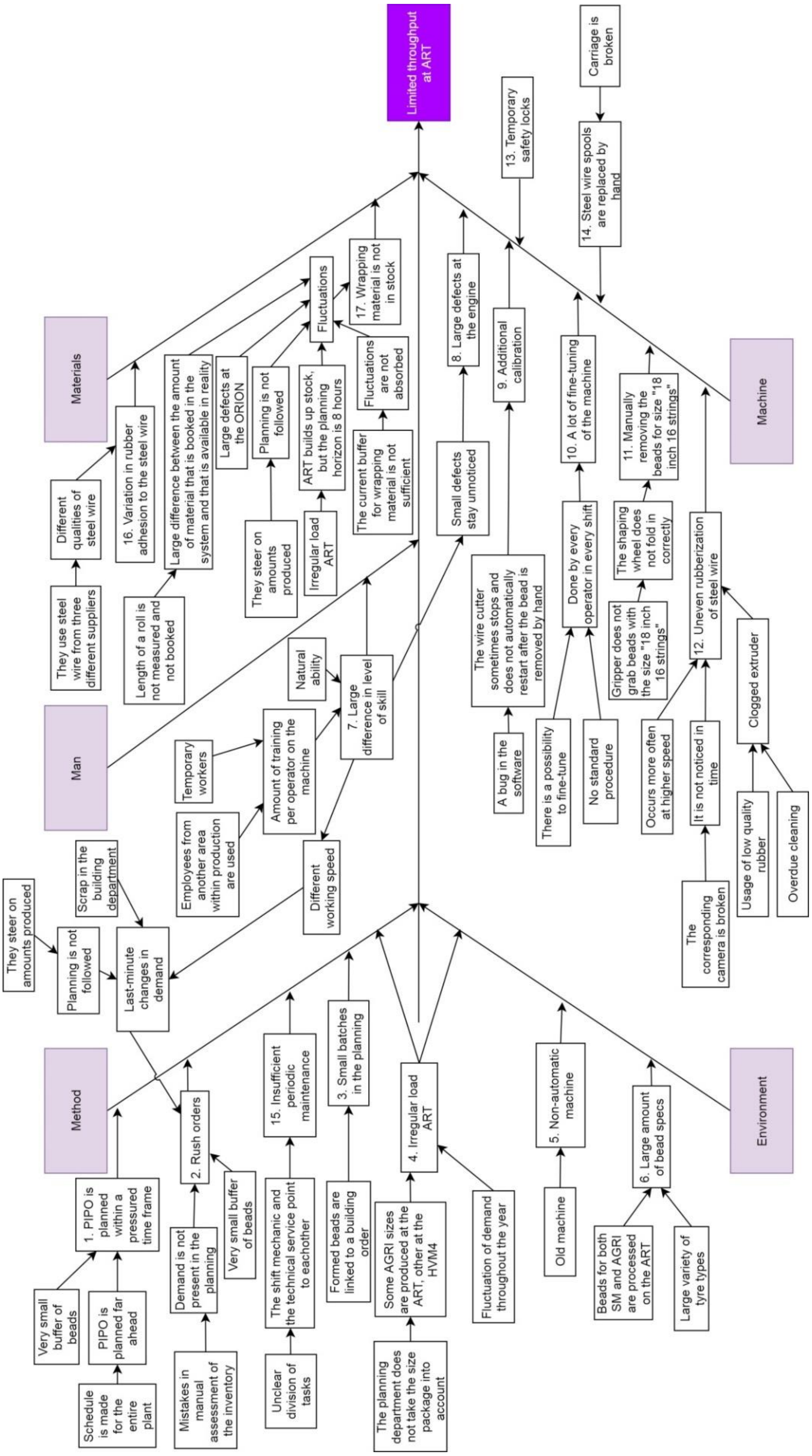


Figure 5.3: *Ishikawa diagram – Limited throughput at the ART.*

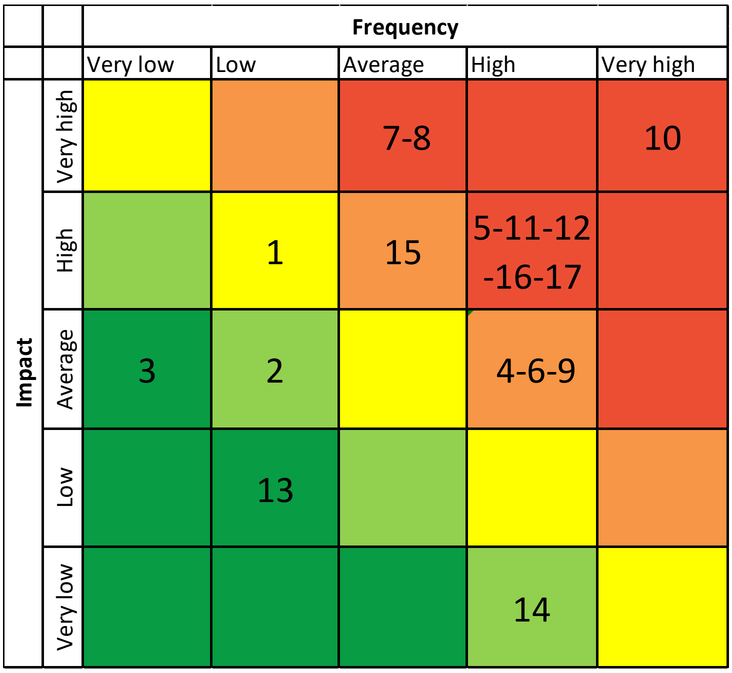
***Table 5.4**: Potential causes.*

#	Categorization	Cause	Problem statement
1	Method	PIPO (Periodieke Inspectie Preventief Onderhoud) within a time period that has an extraordinarily high workload	The PIPO can be scheduled in a time period that has an extraordinarily high workload, because the PIPO is planned far ahead. There is only a small buffer (safety lead time) of beads to limit the impact, which makes the timing of the PIPO very important.
2	Method	Rush orders	Rush orders lead to an inefficient plan.
3	Method	Small batches	Beads are made-to-order resulting in small batches (that can be grouped manually). This creates additional and sometimes unnecessary changeovers.
4	Method and Environment	Irregular load at ART	The workload at the ART is irregular.
5	Environment	Non-automatic machine	It is an old machine that requires a lot of work from operators. A new machine is very expensive resulting in the old machine being almost the only option.
6	Environment	Large amount of bead specs	The large amount of specs, which is a unique selling point of the company, leads to many changeovers.
7	Man	Large difference in level of skill of operators	Not every operator at the ART has the desired level of skill, resulting in low working speed and sometimes even large defects.
8	Machine	Major machine failure	Small defects are not noticed leading to major machine failure.
9	Machine	Additional calibrating	Unnecessary calibrating, caused by a bug in the program, takes up too much time. This is unnecessary because it is a machine failure (not because it is preventive calibrating).
10	Machine	Fine-tuning of the machine	Continuously fine-tuning the machine according to personal preferences of the operator takes too much time.
11	Machine	Manually removing beads	A certain type of defect that results in manually removing beads of a certain size, which is time consuming.
12	Machine	Uneven rubberization of steel wires	Uneven rubberization leads to scrap.
13	Machine	Temporary safety locks	Opening temporary safety locks, which close fences that are placed around moving obstacles, take more time than regular safety locks.
14	Machine	Steel wire is replaced manually	Replacing steel wire manually takes more time than with a carriage, a device that rolls the spool in place.
15	Method	Insufficient periodic maintenance	Unclear division of tasks, which results in insufficient periodic maintenance.

16	Materials	Variation in rubber adhesion to the steel wire	Different qualities of steel wire are used resulting in varying rubber adhesion to the steel wire.
17	Materials	No wrapping material available	Fluctuations in supply and demand cause a shortage of wrapping material, because the current buffer is not sufficient to absorb fluctuations.

***Table 5.5**: Relationships between causes.*

Sub-cause	**Related causes**
Large difference in level of skill of operators	2, 7, 8
They steer on amounts produced	2, 17
Irregular load at ART	4, 17
Very small buffer of beads	1, 2
Unclear responsibilities and tasks	10, 15



		Frequency				
		Very low	Low	Average	High	Very high
Impact	Very high			7-8		10
	High		1	15	5-11-12 -16-17	
	Average	3	2		4-6-9	
	Low		13			
	Very low				14	

***Figure 5.4:** Probability-Impact Matrix.*

wrapping material available. Improving any of these causes has a high impact on the throughput at the ART. Cause 10, fine-tuning of the machine, has the highest importance. The other causes in the red area have similar importance, because they are on the same diagonal. From Figure 5.3 we see that we should limit the possibilities to fine-tune to decrease the amount of time that is spent on fine-tuning of the machine (cause 10). First, by creating an agreed upon setting or settings, if (for example) different sizes require different settings. Second, by making some settings that do not have to be accessible non-accessible for operators. This solution requires a very thorough understanding of the machine and the effects of certain components. In contrast to the process technologist, we do not have that understanding. Because the knowledge is already present within Vredestein, we do not continue to improve this cause and give the process technologist the recommendation to continue. We further elaborate on the implementation of the recommendation in Chapter 6. The other causes within the red area have a similar level of importance. We decide to focus on cause 17: no wrapping material, because the sub-causes are more related to our field of expertise and there we could contribute most. The other causes in the red area have technical issues that are material or machine specific. Here the same reasoning applies, it is not related to our field of expertise and the knowledge is present within Vredestein. We communicate these causes with the business team manager who can allocate the issues to the employees with the right skills. Thus, finding solutions for (some of) the other causes is a recommendation for further research if the ART remains the bottleneck. To validate our choice, we assess the impact of wrapping material on starvation at the ART. We cannot validate all causes in the probability-impact matrix, because some are not booked or the bookings do not specify whether it is a problem. For instance, the amount of fine-tuning is booked, but we do not know which part is required and which part is not necessary. Thus, this number does not indicate if the fine-tuning can be reduced. For starvation on wrapping material we know every minute is a loss that is not necessary. From the data, period 14/1/2019-31/3/2019, we gather the total amount of booked starvation caused by wrapping material. This adds up to 1,050 minutes of starvation caused by wrapping material. The total available time is 110,400, which means that we gain 0.95% of time if we can eliminate starvation caused by wrapping material.

We see from Figure 5.3 that we can tackle five sub-causes to improve the throughput at the ART caused by no wrapping material. These five sub-causes are the following:

- Length of a roll wrapping material is not measured and not booked
- Large defects at the ORION
- Vredestein steers on amounts produced
- Irregular load at the ART
- The current buffer for wrapping material is not sufficient

We do not look into the irregular load at the ART, because this only causes a shortage of wrapping material if the ART is ahead of schedule, see Appendix 3. Also, we do not look into large defects at the ORION, because it is a technical issue of the machine and not our field of expertise. If this is still an opportunity for improvement after improving other sub-causes it can be allocated to the employees with the right skills. Their current KPIs motivate to produce high amounts of tyres, but not necessarily to deliver the demand of the next station. The impact it has on the throughput of the system is unclear, but it is identified as an issue throughout the entire factory. The project team has decided to revise the current KPIs according to the concept of TOC. They started for PCT and plan to continue for AGRI and SM. Thus, we do not look into revising the current KPIs. This leaves us with two sub-causes to improve. The first sub-cause is “the length of a roll of wrapping material is not measured and not booked”. The second sub-cause is “the current buffer for wrapping material is not sufficient”. Improving these sub-causes results in ensuring the right materials at the right time.

5.3 Subordinate non-bottleneck processes

In this section we execute the two phases of the process to subordinate all non-bottleneck processes. We start with Phase 6 in Section 5.3.1. In this section we discuss data on the length of a roll of wrapping material. Section 5.3.2 continues with Phase 6 by setting up the inventory control policy. Section 5.3.3 executes Phase 7 and gives options for implementation and recommendation.

5.3.1 Phase 6: Ensure the needed materials - a roll of wrapping material

In Phase 6 we decide how to improve the shortage of wrapping material at the ART. First, we gather data on internal demand uncertainty that is caused by scrap. The varying length of a roll of wrapping material and the number of rolls that are cut from half a calendar roll are uncertainties caused by scrap in previous production processes. From here on, the length of a roll of wrapping material is mentioned as X and the number of rolls that can be cut out of half a calendar roll as Y. We gather data on stochastic variable X using the measurement method described in Section 4.4.1. Due to the limited time to gather data, we have a small dataset of 27 data points. Therefore, we recommend to gather more data to check the conclusion that is based on this small dataset. We use a boxplot to define outliers. Figure 5.5 shows the boxplot and Table 5.6 gives the boxplot statistics. The minimum and maximum are defined by respectively $Q1 - 1.5 * IQR$ and $Q3 + 1.5 * IQR$, where $Q1$ is the first quartile, $Q3$ is the third quartile and IQR (the inter quartile range) $= Q3 - Q1$.

Using the boxplot, we identify four data points as outliers. We do not take these data points into account for determining the distribution of X. We do recommend gathering more data to see whether or not the outliers occur regularly or if they are incidental. Nevertheless, four outliers are a relatively large part of the data set because the data set is small. Because the outliers are a relatively large part of the data set and very small rolls can have a negative impact on the shortage of material, we decide to come up with another solution to cope with very small rolls. We discuss the solution in Section 5.3.3. The outlier that is a large roll does not have a negative impact on the shortage of material, which is why we decide not to come up with another solution to cope with very large rolls.

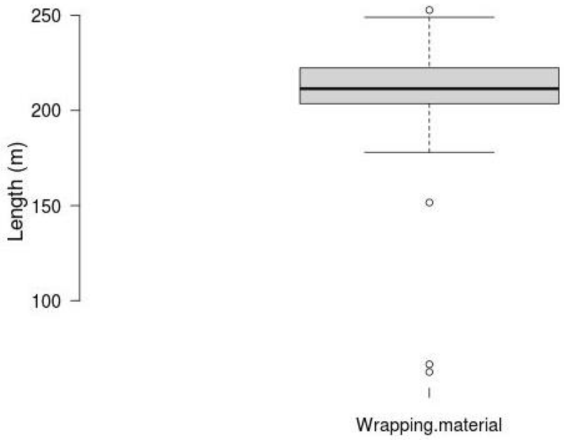


***Figure 5.5**: Boxplot: length of a roll of wrapping material.*

***Table 5.6:** Boxplot statistics.*

Maximum	249.95
3rd quartile	222.35
Median	211.43
1st quartile	203.95
Minimum	176.35

***Table 5.7:** Shapiro-Wilk test results.*

n	23
α	0.05
$\bar{x}$	216.09
W	0.9207
p-value	0.0689

To check if X is normally distributed, we test the data using the Shapiro-Wilk test. Table 5.7 displays the results from the Shapiro-Wilk test. Since p-value > α, we assume that the data is normally distributed. In other words, the difference between the data sample and the normal distribution is not big enough to be statistically significant.

The 2nd and 3rd column of Table 5.8 display the characteristics of X (μ_X and σ_X). We see that the average length on a roll is lower than the assumption of 250 meter. To decide whether we should update the assumption of 250 meters per roll, we conduct a left tailed hypothesis test. In the test we set $H_0: \mu \geq 250$ and $H_1: \mu < 250$, where the level of significance, α, equals 1%. We know the standard deviation of the sampling test, but we do not know the standard deviation of the population. Thus, we use a t-distribution with $n-1$ degrees of freedom (df). Table 5.9 shows the results of the left tailed hypothesis test. From the table follows that the critical region is $(-\infty, 243.7]$. $\bar{X} = 216.1$ meters and is within the critical region, therefore we reject H_0. This means that we do want to update the assumption of 250 meters per roll. We set the expected length of a roll of wrapping material to the rounded average of the sampling test, which equals 216 meters.

***Table 5.8**: Characteristics of wrapping material.*

Name	$\boldsymbol{\mu_X}$	$\boldsymbol{\sigma_X}$	$\boldsymbol{\mu_Y}$	$\boldsymbol{\sigma_Y}$	$\boldsymbol{E(XY)}$	$\boldsymbol{VAR(XY)}$
HE01-00-0034	216.09	12.05	9.53	0.50	2060.55	24859.73
HE01-00-0038	216.09	12.05	8.26	0.44	1783.85	18803.20

***Table 5.9**: Hypothesis test results.*

n	23
df	22
α	0.01
z	-2.508
x_k	243.7
$\bar{X}$	216.1

The number of rolls that can be cut out of half a calendar roll, *Y*, has a discrete distribution. From data on historic orders of wrapping material (that is already available) we gather the following: for HE01-00-0034, 9 rolls can be cut from half a calendar roll with a chance of 0.46 and 10 rolls with a chance of 0.54. For HE01-00-0038 8 rolls can be cut from half a calendar roll with a chance of 0.74 and 9 rolls with a chance of 0.26. Next, we calculate μ_Y and σ_Y , the mean and standard deviation of the number of rolls per batch, using Equation 5-1. We add the characteristics of *Y* (μ_Y and σ_Y). in Table 5.8. The variation in the number of rolls does not affect the accuracy of the inventory in the system, because each roll is booked.

***Equation 5-1**: Mean and standard deviation in case of a discrete distribution.*

$$\boldsymbol{\mu} = \sum_i^n p_i x_i$$
$$\boldsymbol{\sigma} = \sqrt{\sum_i^n p_i (x_i - \mu)^2}$$

p_i: $Probability\ of\ x_i$
x_i: $Value\ of\ i$

If we combine the amount of meters per roll and the number of rolls per batch, we get the amount of meters per batch. To do so, we use Equation 5-2 . We can use these formulas, because *X* and *Y* are independent and, as mentioned in Section 2.7, all rolls within a batch have the same length. We add the characteristics of the amount of meters per batch in Table 5.8.

Equation 5-2: *Expected value and variation for the product of independent X and Y.*

$$\boldsymbol{E}(\boldsymbol{XY}) = E(X) * E(Y)$$
$$\boldsymbol{VAR}(\boldsymbol{XY}) = E[X^2] * E[Y^2] - E[X]^2 * E[Y]^2$$
$$Because: VAR(XY) = E[X]^2 VAR[Y] + E[Y]^2 VAR[X] + VAR[X]VAR[Y]$$ (Goodman, 1960)
$$And: VAR(X) = E[X^2] - E[X]^2$$

X: $amount\ of\ meters\ per\ roll$
Y: $number\ of\ rolls\ per\ batch$

5.3.2 Phase 6: Ensure the needed materials – inventory control policy

Next, we implement the inventory control policy. In literature, most formulas are based on external demand uncertainty. We encounter internal demand and supply uncertainty that influence the uncertainty mentioned in the formula descriptions. All of the SKU characteristics and inventory control parameters that we mention in the following paragraphs are later summarized in respectively Table 5.10 and Table 5.11.

We calculate the economic order quantity (EOQ) with Equation 3-6. The holding cost for wrapping material is unknown within Vredestein. The holding cost per unit and time unit is often determined as a percentage of the unit value. A typical carrying charge could be something like 10 to 15 percent if we use one year as the time unit (Axsäter, 2015). Because we do not know the holding costs, we decide to use the typical carrying charge of 15% defined by Axsäter (2015). The unit values of HE01-00-0034 and HE01-00-0038 are respectively €0.10 and €0.12 per meter. We define the order cost as the set-up time (in hours) multiplied with the machine cost per hour. The machine cost includes machine, labor and overhead costs. The setup time is 7 minutes and the machine cost is €89 per hour. Thus, the cost per order or setup = 89*7/60 = €10.38. This results in the following formula for the economic order quantity: $EOQ_i = \sqrt{\frac{2*10.38*D_i}{v_i*0.15}}$, where D_i is the annual demand for SKU *i* in rolls and v_i is the unit cost of SKU *i* in euros. This results in $EOQ_1 = 104$ and $EOQ_2 = 211$ rolls.

Next, we use a heuristic to determine the optimal order quantity and safety stock while taking the storage capacity and batch size into account.

We determine the optimal order quantity (*Q**), which takes the storage capacity into account, with the method described by Nahmias and Olsen (2015). First, we check if the storage capacity constraint is active or not. The constraint is active if $\sum_{i=1}^{2} c_i EOQ_i > C$, where c_i is the space consumed by one unit of product *i* for *i*=1,2 and C is the total storage space available in rolls. The space consumed by one unit is for both SKUs equal to one unit of material handling equipment (MHE). Thus, $c_1 = c_2 = 1$ and $c_1 EOQ_1 + c_2 EOQ_2 = EOQ_1 + EOQ_2 = 104 + 211 = 215.$ $C = 126$, which is smaller than 215. Thus, the storage capacity constraint is active. Because the ratios $\frac{c_i}{h_i v_i}$ are different, proportional scaling of the EOQ values is not optimal. Thus, we use the Lagrange multiplier θ to determine the optimal order quantity with Equation 3-8. This results in the following formula for the economic order quantity: $Q_i^* = \sqrt{\frac{2*10.38*D_i}{v_i*0.15+2\theta c_i}}$. We can determine the Lagrange multiplier θ using *interval bisection* so that $\sum_{i=1}^{2} c_i Q_i^* = C$. Interval bisection (Teodorescu, Stanescu, & Pandrea, 2013) compares the target value to the middle element of the array. If they are not equal, the half that cannot contain the target is eliminated and the search continues on the remaining half, again taking the middle element to compare to the target value, and iterate this until the target value is found. If the search ends with the remaining half being empty, the target is not in the array. We know that $\theta > 0$, see Section 3.3.6. If we start with $\theta = 1$, we obtain $Q_1^* = 9$ and $Q_2^* = 20$. Thus, $\sum_{i=1}^{2} c_i Q_i^* = 29$ and the capacity is 126, which implies $\theta < 1$. Thus, $0 < \theta < 1$. Next, we check $\theta = 0.5$ and obtain $\sum_{i=1}^{2} c_i Q_i^* = 41$, which implies $\theta < 0.5$. After some iterations, we find the optimal value of $\theta = 0.0444$, and $Q_1^* = 39$ and $Q_2^* = 87$ rolls.

Finally, because we order in batches, we round the optimal order quantity *Q** to a multiple of the batch size and obtain the order quantity *Q*. There is variation in the batch size, i.e. the number of rolls that can be cut out of half a calendar roll (see Section 5.3.1). We choose to round Q* to the maximum number of rolls that can be cut out of half a calendar roll to ensure that there is enough space to store all items. This means that for HE01-00-0034 we round to a multiple of 10 and for HE01-00-0038 to a multiple of 9. We compare the total costs of holding and setup for the neighboring solutions that possibly do not violate the storage capacity constraint, which are $Q_1 = 30$ and $Q_2 = 90$, $Q_1 = 40$ and $Q_2 = 81$, and $Q_1 = 30$ and $Q_2 = 81$, to determine the optimal order quantity. Using the formula $TRC(Q) = \frac{AD}{Q} + \frac{hvQ}{2}$ (Silver et al., 2016), we obtain $TRC(Q_1 = 30) + TRC(Q_2 = 90) = 1{,}766.19$, $TRC(Q_1 = 40) + TRC(Q_2 = 81) = 1{,}727.31$, and $TRC(Q_1 = 30) + TRC(Q_2 = 81) = 1{,}855.78$. All solutions do not violate the storage capacity constraint and the second solution has the lowest costs. Thus, we set Q_1 to 40 and Q_2 to 81 rolls. In the system, this results in $Q_1 = 8{,}643.5$ and $Q_2 = 17{,}503.1$ meters.

With the fill rate (P_2) as service measure (see Section 4.4.1), we calculate *G(k)* with Equation 3-9. The company defines the desired fill rate. The desired fill rate is not an exact value that they calculate. Because they deal with a bottleneck, they want the fill rate to be close to 100%. Therefore, we set the fill rate to 99.5% and perform a sensitivity analysis with a fill rate of 99.0% and 99.9%. The minimum value of *k* is 0, because we cannot have a negative safety stock *SS.* Given Equation 3-9, we calculate the Normal loss function *G(k)*. We retrieve the value of *k* from the Normal probability distribution table (Silver et al., 2016, Table II.1, Appendix II).

Furthermore, we calculate the *SS* and σ_{L+R} with Equation 3-1. Here, σ_{L+R} includes internal demand and internal supply uncertainties. As mentioned in Section 2.7, the lead time (*L*) is 4 to 8 hours. The expected lead time is defined by the planner, because there is no available data on lead times. We assume the lead time is normally distributed with $\mu_L = 0.75$ shifts and $\sigma_L = 0.125$, such that 95% of the actual lead times fall into the expected interval. We have a periodic review, where the review period (*R*) is equal to one shift, see Section 4.4.1. The standard deviation of demand (*m*), including internal demand uncertainty, in one period of time (σ_D) is calculated using the standard deviation of the amount of meters per batch ($\sqrt{VAR(XY)}$ from Table 5.8) multiplied with the average demand in batches during one shift ($D_1(b)$). Because we do not book per meter but per roll (presented in meters), we round the safety stock in meters up to entire rolls, based on the average length on a roll. This results in $SS_1 = 0$ and $SS_2 = 216.1$ meters

If $Q_1 + Q_2 + SS_1 + SS_2 \leq C$, we have a feasible solution and complete the inventory control policy. If $Q_1 + Q_2 + SS_1 + SS_2 > C$, we do not have a feasible solution. We recalculate the order quantities with an updated storage capacity constraint $C_{updated} = C_{original} - SS_1 - SS_2$, k, and SS and check if $Q_1 + Q_2 + SS_1 + SS_2 \leq C_{original}$. Then, we repeat this cycle until we find a feasible solution. In this case $Q_1 + Q_2 + SS_1 + SS_2 = 122$ rolls, which is smaller than the storage capacity of 126 rolls. Thus, we have a feasible solution and continue with calculating the reorder point.

The reorder point (s) is defined by Equation 3-5. Because we have advance demand information, the expected demand during the lead time and review period ($\hat{x}_{L+R}$) changes over time. This means that the reorder point is a dynamic parameter. The reorder point is expressed in meters.

Table 5.10 shows all of the previously mentioned SKU characteristics and Table 5.11 gives a summary of the inventory control parameters. We specify for each parameter in the tables whether it is expressed in meters (m), rolls (r), batches (b), shifts (s) or euro's $(€)$. Next, we determine the expected performance of the inventory control system. Table 5.12 shows the system performance for a period of one year. First, we calculate the realized k and *G(k)*, based on the rounded safety stocks in rolls using Equation 3-3 and Equation 3-9. Then, we calculate the fill rate, cost of inventory, expected yearly shortage, and the average stock level, as explained at the end of Section 4.4.1.

***Table 5.10**: SKU characteristics.*

Name	$v(€)$	$A(€)$	$R(s)$	$L(s)$	$\sigma_L(s)$	$\sigma_D(m)$	$Target\ P_2$
HE01-00-0034	0.10	10.38	1	0.75	0.0156	25.2	0.9950
HE01-00-0038	0.12	10.38	1	0.75	0.0156	126.7	0.9950

***Table 5.11**: Summary inventory control.*

Name	$D(m)$	$D_{L+R}(m)$	$D_1(b)$	$\sigma_{L+R}(m)$	$G(k)$	$EOQ(r)$
HE01-00-0034	361,305.2	577.4	0.16	79.5	0.543	104
HE01-00-0038	1,805,244.0	2,885.1	0.92	397.7	0.220	211

Name	k	$SS(r)$	$SS(m)$	$Q^*(r)$	$Q(r)$	$Q(m)$
HE01-00-0034	0	0	0	39	40	8,643.5
HE01-00-0038	0.43	1	216.1	87	81	17,503.1

***Table 5.12**: System performance.*

Name	HE01-00-0034	HE01-00-0038	Total
k	0	0.81	x
$G(k)$	0.399	0.117	x
P_2	0.9976	0.9982	0.9981
$TC(€)$	498.86	1,232.34	1,731.20
$ES(m)$	885.0	3,216.5	4,101.6
$Average\ stock\ level\ (r)$	20	41.5	61.5
$Average\ stock\ level\ (m)$	4,321.7	8,967.6	13,289.4

Validation of the model

To ensure the validity of the results delivered by our model, we use our model with input parameters that represent the current inventory policy and compare the results with the actual values gathered from historic data. We know from historic data that we had 1,050 minutes of starvation/shortage at the ART in the period 14/1/2019-31/3/2019. We do expect our outcome to be lower than the data-based result, because we do not take all types of uncertainty into account. Because the two types of uncertainty that we discuss are identified as the biggest influence on the process uncertainty, we do expect our outcome to cover a large part of the data-based result. We model the current inventory policy with the following assumptions. First, we assume a standard deviation based on their current assumption that one roll contains 250 meters. We know that rolls did not contain 250 meters, but their inventory system did calculate with 250 meters. Thus, to validate the current inventory policy it is better to base the standard deviation on their current assumption that one roll contains 250 meters than the average length of 216 meters. Second, we use a safety stock that approximates the safety lead time of two hours. Third, we set the order quantity to the average order quantity gathered from historic data. The current inventory policy leads to the results presented in Table 5.13. The expected shortage in meters in Table 5.13 (30,870.7) is for one year, thus the expected shortage (m) for the period 14/1/2019-31/3/2019 is 6,512.4 meters. Using a weighted average, we convert the expected shortage in meters into minutes. The expected shortage equals 893.7 minutes of starvation at the ART. This outcome meets our expectations. We do not know the reason of the shortages that occurred in the past, which is why we cannot validate the exact number for shortages caused only by uncertainty in scrap and queue waiting time.

Table 5.13*: Model validation.*

Name	Current inventory policy
$\boldsymbol{P_2}$	0.9858
$\boldsymbol{TC}(€)$	5,754.64
$\boldsymbol{ES}(\boldsymbol{m})$	30,870.7
$\boldsymbol{Average\ stock\ level}\ (\boldsymbol{r})$	19

Sensitivity analysis

Next, we perform two sensitivity analyses. We explain the purpose of the analysis when introducing the analysis because the two analyses have a different purpose. First of all, we are interested in comparing the results of different target P_2. Target P_2 is not a fixed value and we are interested in the trade-off between a higher fill rate and its consequences. We compare three different values for $Target\ P_2$: 99.0%, 99.5% and 99.9%. We repeat the calculation of all parameters, as demonstrated earlier in this section, given that $Target\ P_2$ is 99.0% or 99.9% instead of 99.5%. Table 5.14 presents the results.

Table 5.14*: Sensitivity analysis on the Target P_2.*

$\boldsymbol{Target\ P_2}$	0.9900	0.9950	0.9990
$\boldsymbol{SS_1}(\boldsymbol{m})$	0	0	216.1
$\boldsymbol{SS_2}(\boldsymbol{m})$	0	216.1	432.2
$\boldsymbol{P_2}$	0.9945	0.9981	0.9997
$\boldsymbol{TC}(€)$	1,727.31	1,731.20	1,738.33
$\boldsymbol{ES}(\boldsymbol{m})$	11,815.9	4,101.6	597.7
$\boldsymbol{Average\ stock\ level}\ (\boldsymbol{r})$	60.5	61.5	63.5
$\boldsymbol{Average\ stock\ level}\ (\boldsymbol{m})$	13,073.3	13,289.4	13,721.6

We see that the change in fill rate has a small effect on both costs and stock level. This is caused by the margin of capacity left unutilized with the order quantity rounded to batches. The safety stock uses this excess of capacity and therefore the order quantity stays the same. Furthermore, the amount of safety stock needed to achieve those service levels are relatively small.

Next, we perform a sensitivity analysis for the carrying charge. The carrying charge of 15% is based on a rule of thumb and does not necessarily represent the real cost of inventory. To see the influence of this assumption on the relevance of our inventory control policy, we perform a sensitivity analysis. Table 5.15 presents the results of the sensitivity analysis. Changing the carrying charge to 10-40% only changes the costs, because the storage capacity also limits the order quantity for these values (not the EOQ). This means that the defined policy is still relevant if the carrying charge deviates slightly and only the costs change.

***Table 5.15**: Sensitivity analysis on the carrying charge*

$\boldsymbol{h}$	0.10	0.15	0.20	0.40
$\boldsymbol{P_2}$	0.9981	0.9981	0.9981	0.9981
$\boldsymbol{TC}(€)$	1,655.78	1,731.20	1,806.61	2,108.27
$\boldsymbol{ES(m)}$	4,101.6	4,101.6	4,101.6	4,101.6
$\boldsymbol{Average\ stock\ level\ (r)}$	61.5	61.5	61.5	61.5
$\boldsymbol{Average\ stock\ level\ (m)}$	13,289.4	13,289.4	13,289.4	13,289.4

5.3.3 Phase 7: Implementation and recommendations

In Phase 7 we discuss the recommendations for implementation. All recommendations that require an alteration in PIBS are discussed with an employee who can implement alterations. He confirmed that all options discussed below are possible concerning PIBS.

First, we recommend to change the assumption of 250 meters per roll of wrapping material to 216 meters to increase the accuracy of the inventory. This requires a change in PIBS. The amount of meters that are automatically booked per roll can easily be changed in PIBS.

We recommend to expand this option with a solution for the small rolls that are identified as an outlier in Section 5.3.1. For these small rolls, we do want to adjust the amount of meters per roll in the system. We can measure the diameter manually, as described in Section 4.4.1, and estimate the length of the roll using Equation 4-1. The operator can use the template that will be hanging in the working area of the ORION to identify the outliers. The template shows the minimum size of a roll, 176 meters, without becoming an outlier. The operator can hold the roll in front of the template. If the roll is smaller than the roll on the template, the diameter should be measured and entered in the system manually. This solution requires a new template, and alternation in PIBS to enable entering the amount of meters manually. A proposition for the template is given in Appendix 5.

If the shortage of wrapping material has improved sufficiently (by assessment of Apollo Vredestein), we recommend to maintain this solution. If it has not improved sufficiently, we recommend to measure the length of a roll in each batch. This will increase the accuracy of the inventory in the system, but it comes at a cost. There are two options to add a measurement to the roll. First, we can measure the diameter manually and enter the diameter in PIBS and with that estimate the corresponding length. This option does not need an initial investment, but requires time from the operators. Implementing this option also requires alternation in PIBS. We need to add an option to enter the amount of meters manually. Second, we can install measuring equipment at the ORION. The measuring equipment measures the length of the wrapping material while it rolls up the material on the material handling equipment. This option requires an initial investment but does not include additional tasks for the operators. The second option also requires alternation in PIBS, because the data gathered by the measurement equipment needs to be processed in PIBS.

Regarding the inventory control policy we recommend to implement a (R,s,Q) policy as described in Section 5.3.2. With a small amount of safety stock we see a large improvement in the amount of shortage compared to the current policy mentioned in the validation of the model. We recommend to set the target of P_2 to 0.999. From the sensitivity analysis we see that increasing the fill rate requires a small amount of extra stock and a small increase in costs. The needed storage space is already available, which means that the required investment is low. Implementing the policy in PIBS requires small changes. Only the order quantity needs to be adjusted to $Q_1 = 8{,}643.5$ and $Q_2 = 17{,}503.1$, and the current reorder point needs to increase with a safety stock of $SS_1 = 216.1$ or $SS_2 = 432.2$ meters.

5.4 Conclusion

In this chapter we implemented the model. In Section 5.1 we executed the bottleneck identification process. In Phase 1 we excluded machines with a GAP > 50%. In Phase 2 the turning point method identified the ART as the most significant bottleneck. In Phase 3 the utilization method also identified the ART as the most significant bottleneck. Finally, Phase 4 stated that Phases 2 and 3 coincide and concluded on the ART as the most significant bottleneck. We validated the outcome with the knowledge of the daily state of affairs.

In Section 5.2 we executed the bottleneck optimization process. We formulated the problem as “limited throughput at the ART”. We presented an overview of the potential causes using an Ishikawa diagram and we arranged the potential causes in a Probability-Impact Matrix. Using this matrix, we decided to focus on the cause “no wrapping material” and specifically on the two sub-causes “the length of a roll is not measured and not booked” and “the current buffer for wrapping material is not sufficient”.

In Section 5.3 we executed the process to subordinate all non-bottleneck processes. First, we gathered and analyzed the data on the length of a roll of wrapping material. We concluded that the assumption by Apollo Vredestein of 250 meters on a roll should be updated to 216 meters. Second, we set up an (R,s,Q) inventory control policy and presented the parameters. We also presented the performance of the system, we validated the model and performed a sensitivity analysis. Finally, we provided recommendations regarding wrapping material and the inventory control policy.

6. Conclusion, recommendations and discussion

In this chapter we conclude on the main research questions in Section 6.1. In Section 6.2 we give an overview of the recommendations made throughout this research. Finally, Section 6.3 discusses the limitations of this research.

6.1 Conclusion

To achieve both lower costs per tyre and a higher throughput, we decided to improve performance by following the concept called Theory of Constraints. In this section we answer the main research question:

"How can Apollo Vredestein identify the most significant bottleneck machine within the production line of agricultural and space master tyres, improve the most significant bottleneck machine, and align non-bottleneck machines to increase the throughput of the system?"

To identify the most significant bottleneck we developed a bottleneck identification process. The bottleneck identification process consists of four phases. The first phase filters on data availability to identify non-bottlenecks. The second phase performs the turning point method and the third phase performs the utilization method to identify the most significant bottleneck. Finally, the fourth phase gives a conclusion on the location of the bottleneck and validates the result. Apollo Vredestein can identify the most significant bottleneck by using the supportive dashboard (see Appendix 2) while executing these phases.

In the current situation we concluded that the most significant bottleneck is a machine called the ART. The ART is a bead-making machine that produces both AGRI and SM beads. We have found multiple causes that Apollo Vredestein can improve to achieve a high impact on the throughput at the ART. Nevertheless, fine-tuning of the machine has the highest importance. To decrease the amount of time that is spent on fine-tuning of the machine, Apollo Vredestein should limit the possibilities to fine-tune. First, by creating an agreed upon setting or settings if (for example) different sizes require different settings. Second, by making some settings that do not have to be accessible non-accessible for operators. Because this solution requires a very thorough understanding of the machine and the effects of certain components, we recommended the process technologist to improve this cause.

Apollo Vredestein can align non-bottleneck machines by improving another cause, namely no wrapping material. Apollo Vredestein can reduce the shortage of wrapping material by improving the accuracy of the inventory of wrapping material and by implementing an inventory control policy to buffer against uncertainties.

In this research, we provided two options to improve the accuracy of the inventory. The first option is adjusting the amount of meters booked per roll of wrapping material from 250 to 216 meters. This solution improves the accuracy with the least effort, but does not offer a precise representation of the inventory. This option can be expanded by manually measuring small rolls that are outliers. These rolls can be identified with a template. Appendix 5 provides an example for the template. After the operator measures the diameter, he or she can manually enter the diameter in PIBS and PIBS estimates the corresponding length. The second option is to measure the length of a roll in each batch. This can be done by manually measuring the diameter of the roll, entering the diameter in PIBS, and with that estimating the corresponding length. This requires time from the operator. It can also be done by adding measuring equipment at the machine where wrapping material is produced: the ORION. This option requires an initial investment for the measuring equipment.

Apollo Vredestein can also reduce the shortage of wrapping material by implementing a (R,s,Q) policy to buffer against uncertainties. Internal supply uncertainty caused by queue waiting time, and internal demand uncertainty caused by scrap are the two major types of uncertainty taken into account for determining the parameters. For SKU HE01-00-0034 the policy has a review period R of one shift, order quantity Q of 8,643.5 meters (40 rolls) and safety stock SS of 216.1 meters (1 roll). For SKU HE01-00-0038 the policy has a review period R of one shift, order quantity Q of 17,503.1 meters (81 rolls) and safety stock SS of 432.2 meters (2 rolls). Given that the amount of meters booked per roll of wrapping material is updated to 216 meters, these parameters result in a weighted average fill rate P_2 of 0.9997. This equals a yearly shortage of 597.7 meters or 82 minutes. From the sensitivity analysis we concluded that this solution had the best trade-off between costs, stock level, and the amount shortage.

6.2 Recommendations

The situation of Apollo Vredestein has changed since the beginning of this research. Here, we shortly update the current situation of Apollo Vredestein, because this influences our recommendations. During the past months, a management decision has led to a significant decrease in the amount of space master tyres produced. This has reduced the work load of the ART and therefore changed the location of the bottleneck. The management decision is a temporary change, but the time interval of this decision is not yet fixed. Thus, we expect the ART to become the bottleneck again in the future, but we do not know when. The future increase in the number of space master tyres produced is a decision influencing the entire production line. Therefore, the change will be announced well on time. In general, the current situation results in the recommendation to implement the easy solutions first, and decide later if the comprehensive solutions are preferred.

Below we present an overview of recommendations made throughout the research. For further details we refer to the corresponding sections. We categorize the recommendations in three sets. The first set of recommendations is directly related to the ART and easy to implement. We therefore recommend to implement them as soon as possible, even though the ART is momentarily not the bottleneck.

- We have used a limited dataset to analyze the length of a roll of wrapping material due to the limited time to gather data. We recommend to gather more data on the length of a roll of wrapping material and, if necessary, update the conclusion, see Section 5.3.1. This can for instance influence the average length of a roll of wrapping material.
- To improve the shortage of wrapping material, we recommend to improve the accuracy of the inventory. We recommend to implement the option to improve the accuracy of the inventory with the least effort, see Section 5.3.3. This option includes adjusting the amount of meters booked per roll of wrapping material from 250 to 216 meters. We recommend to expand this option with manually measuring and booking small rolls that are outliers. If the shortage of wrapping material has improved sufficiently (by assessment of Apollo Vredestein), we recommend to maintain this solution. If it has not improved sufficiently, we recommend to start measuring and booking the length of each roll. Depending on the preference of Apollo Vredestein this can be done by manually measuring the diameter of the

roll and estimating its length, or by automatically measuring the length of the roll with (to be installed) measuring equipment.
- To further improve the shortage of wrapping material, we recommend to implement the (R,s,Q) policy as described in Section 6.1 (and Section 5.3.3).

The second set of recommendations is also directly related to the ART, but implementing them requires further analysis. Because of the current situation, we recommend to implement those recommendations when we know the workload will increase. As we mentioned, this change will be announced well on time.

- We recommend to decrease the amount of time that is spent on fine-tuning the machine, see Section 5.2. Because there is no current guideline on what the settings of the machine should be, reducing the amount of time that is spent on fine-tuning the machine is low hanging fruit.
- After improving the amount of time that is spent on fine-tuning the machine and the amount of shortage, we recommend to check the location of the bottleneck. If the ART remains the bottleneck, we also recommend to improve (some of) the following causes: having a non-automatic machine, different levels of skill of operators, big defects at the engine, manually removing beads, uneven rubberization of steel wires, and variation in rubber adhesion to the steel wire, see Section 5.2.
- We recommend to improve the scanning process. Scanning labels is of high importance and in the current situation the operator needs to scan each roll of the batch. We also know, this does not always happen, which negatively affects the accuracy of inventory. We expect that adding the possibility to scan one roll of the batch instead of each roll in the batch, will increase the amount of rolls that are correctly scanned. We can scan one roll per batch, because all rolls in a batch usually have the same length.

The third set of recommendations contains additional recommendations that we gathered throughout the research that apply to other parts of the production process.

- We recommend Apollo Vredestein to continue to identify the bottleneck in the future, so that they can improve the performance at the right place, see Section 5.1. Furthermore, we recommend to use the dashboard that we provided to support the phases of the bottleneck identification process. The identification of the bottleneck can be done once a month or once every few months. The information can be used during the performance review in the daily performance meetings.
- Based on the bottleneck identification process, we recommend to look into a few other machines as well to gain understanding of reasons behind shortages. These are the TINCH, ORION, BIAS5 and BIAS7, see Section 5.1. The TINCH is a machine that has plenty of spare time, but causes a lot of starvation at the building department. This means that a supporting process is causing the starvation. We recommend to investigate which supporting process causes the starvation. The ORION is a highly utilized machine that causes a small amount of starvation. Because of the high utilization, we recommend to keep some focus on this machine to prevent higher amounts of starvation (at the building department). Finally, BIAS5 and BIAS7 are machines that cause a lot of starvation, and have a high waiting time for service that is not caused by a preceding or succeeding process. This means that there is

either a lack of material handling equipment or there are planned breaks for employees that are not substituted. We recommend to analyze the root cause and improve the process accordingly.

- We recommend to check the curing plan with the capacity of the bottleneck and adapt the plan accordingly. In the current situation the planning process starts at the curing department. The curing department has excess capacity, which leads to a production plan that is over demanding the bottleneck. This creates an unrealistic plan and disturbances in the flow. Adjusting the planning process is an additional aspect that is part of the process to subordinate all non-bottleneck processes (step 3 of the TOC cycle).

6.3 Discussion

There are some limitations in this research that may have influenced the results. These limitations are a point of discussion and we discuss them below.

First, when determining the bottleneck the speed losses are hidden in the gap between available time and the sum of net productive time plus all the losses. This means that we cannot distinguish between speed losses and overdue booking. Because the speed losses are a wide range of losses and there is no data available, we do not know the influence of speed losses on the performance of the stations. It is possible that the speed losses are the biggest loss of the station, but we cannot know with the current dataset. Therefore, it would be interesting to improve the data availability for all stations. This results in the GAP only consisting of speed losses and thus better insight in the effect of speed losses on the performance of the station. If the effect is known, Apollo Vredestein can also act upon it.

Second, when determining the bottleneck we use data on the starvation at a certain station in the production process. We do not know whether or not this starvation resulted in starvation at the curing department. Only starvation at a certain station in the production process that leads to starvation at the curing department is reducing throughput, since Apollo Vredestein plans on curing. Therefore, it would be interesting to know how much of the starvation at the curing department is caused by the starvation of the building department or any other station upstream in the production process. This can influence the outcome of the bottleneck identification process.

Third, the data on the demand of wrapping material is from a period of 11 weeks. Due to seasonality of tyre types, this is not necessary representative for an entire year. If the demand increases or decreases it influences the performance of the proposed inventory policy. With the current order quantity an increase in demand results in an increase in replenishment cycles and therefore an increase in the amount of shortage. On the other hand, a decrease in demand results in a decrease in replenishment cycles and therefore a decrease in the amount of shortage. Thus, the realized performance can deviate slightly. Nevertheless, the validation and comparison with the current situation is representative, because it is based on the same set of data.

Fourth, the division of starvation among the machines in the curing department is currently unknown. These machines are booked as one group of machines, which means that we cannot separate the starvation booked for all curing machines into a starvation per machine. The curing machines are not interchangeable because they are linked to certain molds and sizes. It would be interesting to know if the starvation at curing occurs at specific machines or is divided among all machines. This can create understanding in the causes behind the lack of greentyres.

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Appendix

Appendix 1: Flowcharts with distinction between components

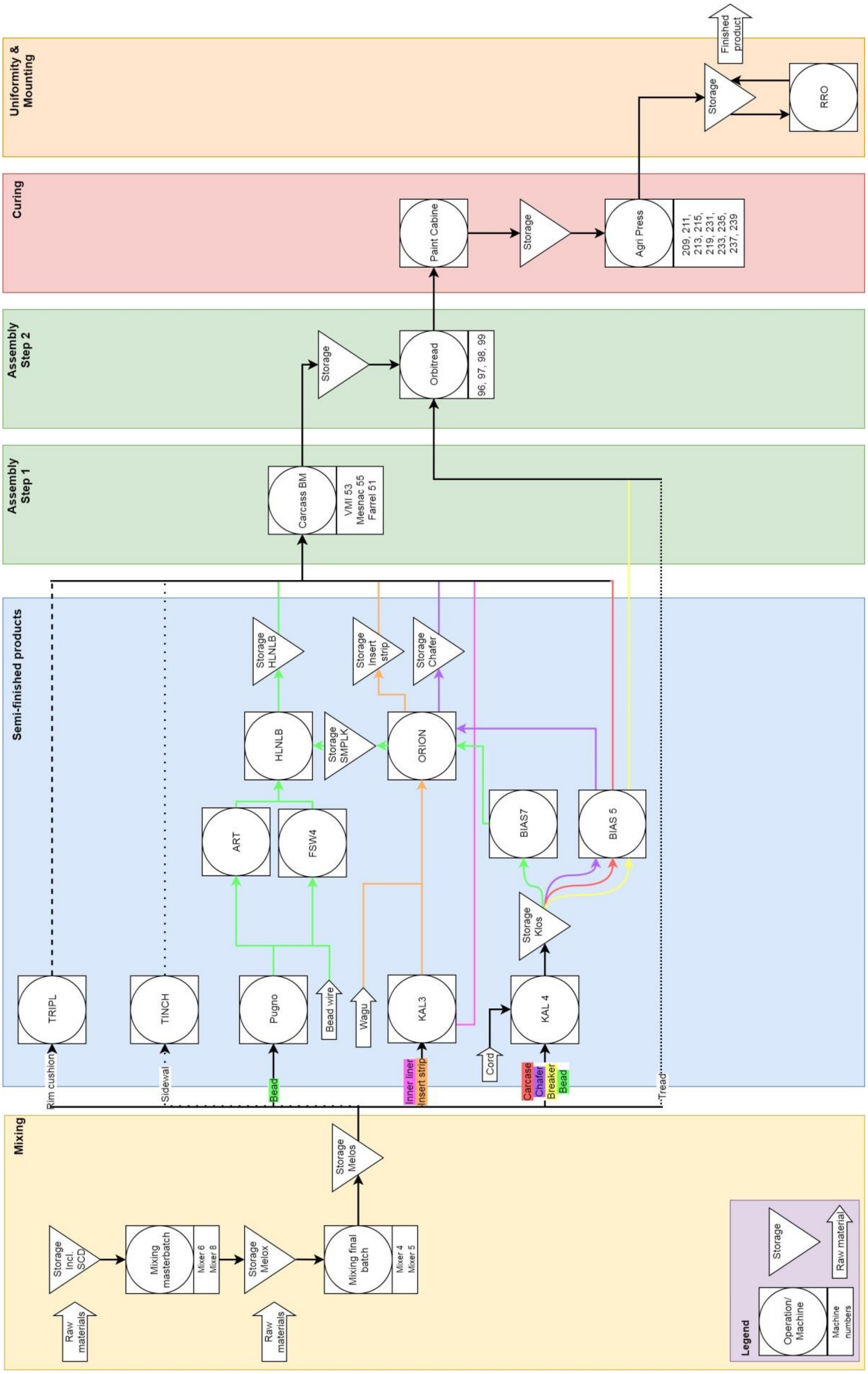


Figure A- 1: Process flow for AGRI tyres.

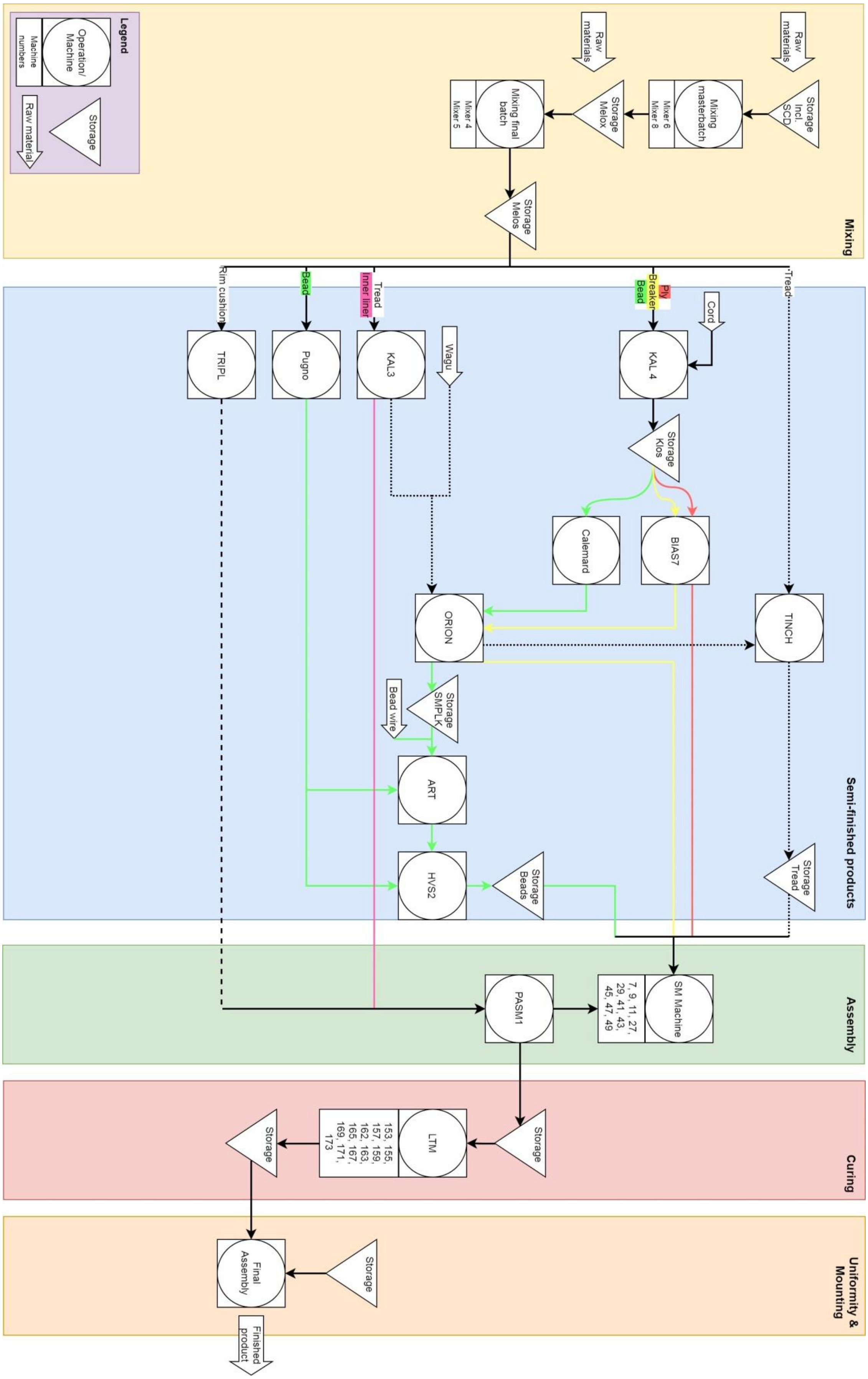


Figure A- 2: *Process flow for SM tyres.*

Appendix 2: Dashboard to identify the bottleneck

The dashboard is a tool that supports the first step of the TOC cycle: Identify the bottleneck. It shows the information needed for the 4 phases of the bottleneck identification process and also indicates some of the outcomes. The dashboard contains 6 pages. The first four pages form the bottleneck identification process and page 5 and 6 give insight on the losses at the bottleneck. Thus, page 5 and 6 are part of the bottleneck analysis and give first insights to start step 2 of the TOC cycle: “optimize the bottleneck”.

The first page “Bottleneck identification” is shown in Figure A- 3. In the upper left corner is a slicer that can be used to filter on the date. Below, information is given about the definitions that are used. Next, the tables for Phase 1-3 are given. The table for Phase 1 shows the machines with a GAP(%)> 50% in green, because they are identified as non-bottleneck machines. The machines identified as non-bottlenecks are left out of the next tables. The second table for Phase 2 shows the machines with TB+ST (%) < 2% in red, because they are identified as a potential bottleneck. The second and third page also support Phase 2, these pages are explained later. The table for Phase 3 shows the utilization per machine and the TB+ST (%) < 2%. This table is sorted on the utilization, which results in the identification of the first machine (highest utilization) that has TB+ST (%) < 2% (which is indicated in red) as the bottleneck. Finally, on the right there is a table that represents Phases 1 to 3. This table gives an overview of the three phases per machine. One additional column, TS(%), is added to show the division between TS and TB.

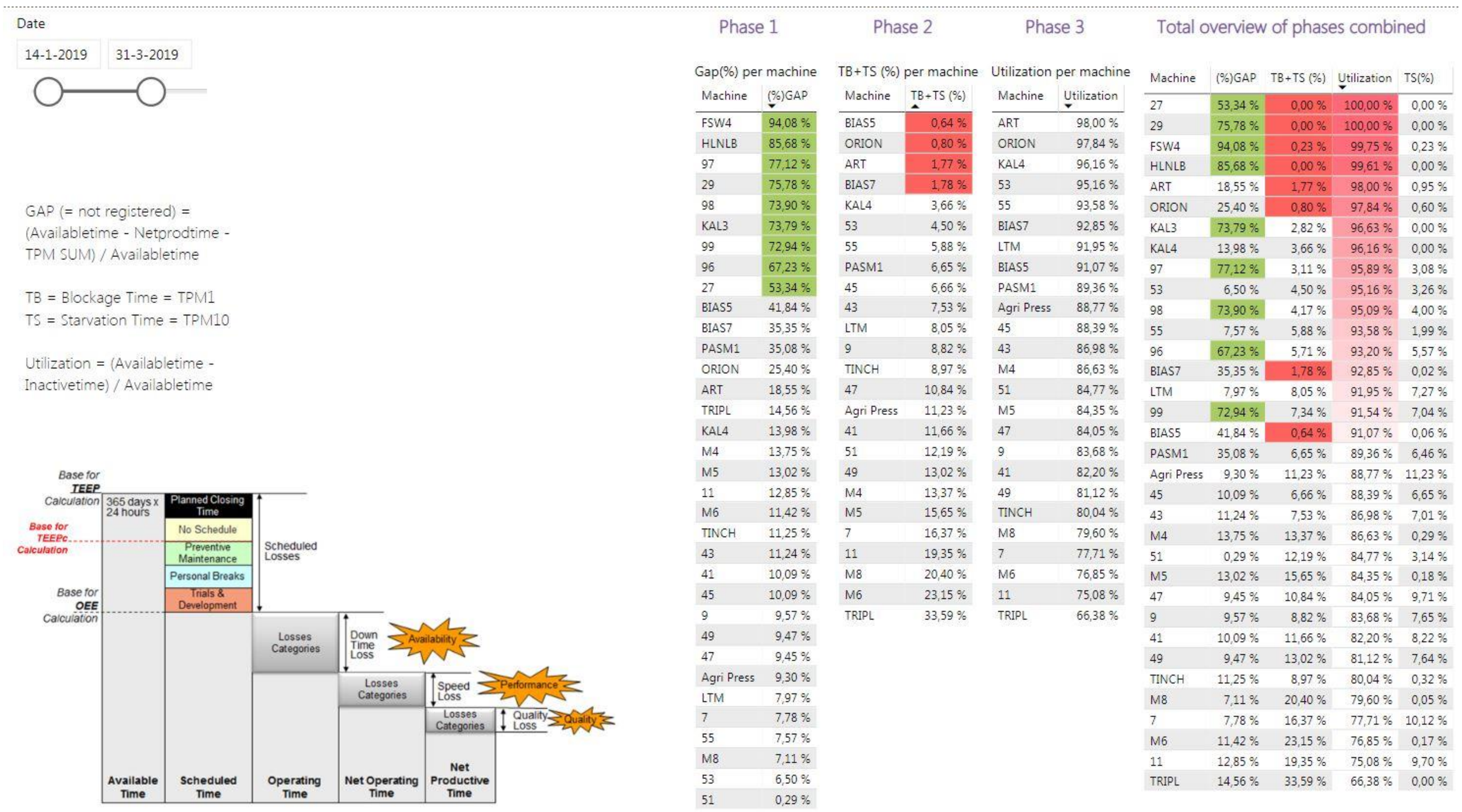
The second page “Visualization Phase 2” represents the visualization of Phase 2. This page is represented in Figure 5.1 (Chapter 5). It shows the TB(%), TS(%) and TB-TS(%) per machine or machine group in the flowchart. This results in the visibility of the principle of the turning point method. It shows a rough pattern starting on the left with positive $\mathrm{TB_i} - \mathrm{TS_i}$, changing into a $\mathrm{TB_i} - \mathrm{TS_i}$ around zero and ending on the right in a negative $\mathrm{TB_i} - \mathrm{TS_i}$. This page is added to create understanding of the method and its variables. In the upper left corner is a slicer that can be used to filter on the date. Below the slicer is a table that (where possible) represents the TB and TS for machines within a machine group. If one of the machine groups is the bottleneck, this table makes the difference in TB and TS visible.

The third page “Caused starvation Phase 2” represents the second part of Phase 2 and is shown in Figure 5.2 (Chapter 5). Here we see the minutes of starvation caused by the machine (instead of the starvation at the machine). Again, the dashboard can be filtered on the preferred dates in the left upper corner. This page is used to see the effect of the machine on succeeding processes. Combining this page with the first page gives a conclusion on the location of the bottleneck (according to the turning point method).

The fourth page “Information starvation” that is represented in Figure A- 4, is a page that is used as input for page 3. This page is not directly needed to identify the bottleneck, but is handy to decide how to adapt the figure when changes occur. It shows the reasons of starvation per station (and per department). In combination with the flowcharts from chapter 3 we find out which machine has caused the starvation. This is used to develop page 3. To include all possible relations this page shows the data of one year. If changes occur and result in changes within the flow or starvation types, it can be found in this page and accordingly altered in page 3.

The fifth page “Machine information” gives information about the bottleneck machine, see Figure A-5. On the left side we can filter on the date, select the bottleneck machine and select the starvation description caused by the bottleneck machine. The information in the upper left corner, within the purple rectangle is fixed. The first graph shows the net production time (%) per week, which indicates the occupation of the bottleneck machine over time. The second graph shows the total downtime (Min) per week for the bottleneck machine. The third graph shows the starvation (Min) per week caused by the bottleneck machine. These graphs provide information on the fluctuation at the bottleneck machine. Also, we use these graphs to check if there is a relation.

The sixth page “Machine losses” gives information about the losses at the bottleneck machine, see Figure A- 6. On the left side we can filter on date and select the bottleneck machine. Because the graphs use two different data sets, we need to select the bottleneck machine twice. The graph in the middle shows the top 5 tpm group losses (Min). The graph on the right shows the losses (Min) of the possible down descriptions within the top 5 tpm groups. These figures give insight on the booked losses at the bottleneck machine.



Date

14-1-2019 31-3-2019

GAP (= not registered) = (Availabletime - Netprodtime - TPM SUM) / Availabletime

TB = Blockage Time = TPM1
TS = Starvation Time = TPM10

Utilization = (Availabletime - Inactivetime) / Availabletime

Phase 1

Gap(%) per machine

Machine	(%)GAP
FSW4	94,08 %
HLNLB	85,68 %
97	77,12 %
29	75,78 %
98	73,90 %
KAL3	73,79 %
99	72,94 %
96	67,23 %
27	53,34 %
BIAS5	41,84 %
BIAS7	35,35 %
PASM1	35,08 %
ORION	25,40 %
ART	18,55 %
TRIPL	14,56 %
KAL4	13,98 %
M4	13,75 %
M5	13,02 %
11	12,85 %
M6	11,42 %
TINCH	11,25 %
43	11,24 %
41	10,09 %
45	10,09 %
9	9,57 %
49	9,47 %
47	9,45 %
Agri Press	9,30 %
LTM	7,97 %
7	7,78 %
55	7,57 %
M8	7,11 %
53	6,50 %
51	0,29 %

Phase 2

TB+TS (%) per machine

Machine	TB+TS (%)
BIAS5	0,64 %
ORION	0,80 %
ART	1,77 %
BIAS7	1,78 %
KAL4	3,66 %
53	4,50 %
55	5,88 %
PASM1	6,65 %
45	6,66 %
43	7,53 %
LTM	8,05 %
9	8,82 %
TINCH	8,97 %
47	10,84 %
Agri Press	11,23 %
41	11,66 %
51	12,19 %
49	13,02 %
M4	13,37 %
M5	15,65 %
7	16,37 %
11	19,35 %
M8	20,40 %
M6	23,15 %
TRIPL	33,59 %

Phase 3

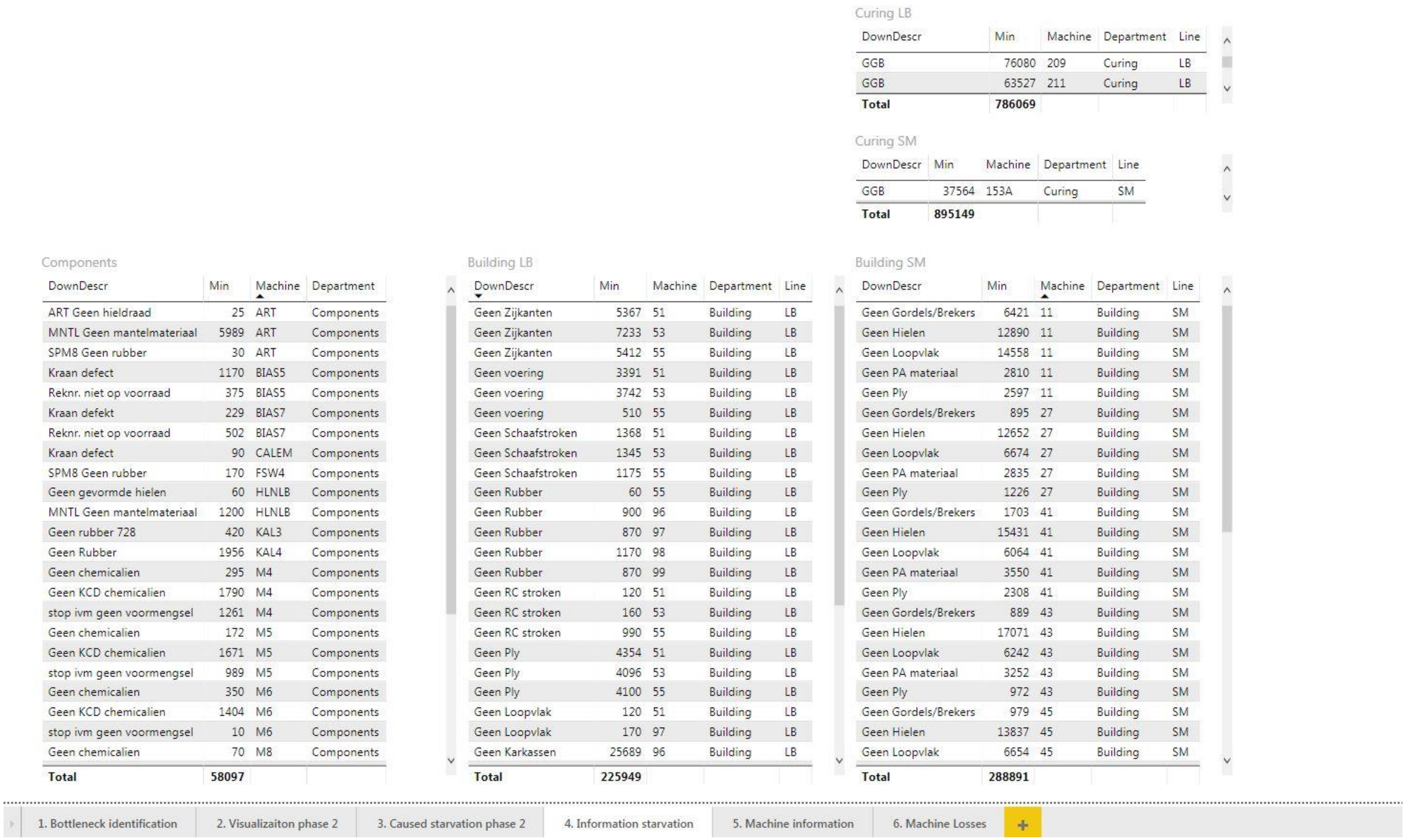
Utilization per machine

Machine	Utilization
ART	98,00 %
ORION	97,84 %
KAL4	96,16 %
53	95,16 %
55	93,58 %
BIAS7	92,85 %
LTM	91,95 %
BIAS5	91,07 %
PASM1	89,36 %
Agri Press	88,77 %
45	88,39 %
43	86,98 %
M4	86,63 %
51	84,77 %
M5	84,35 %
47	84,05 %
9	83,68 %
41	82,20 %
49	81,12 %
TINCH	80,04 %
M8	79,60 %
7	77,71 %
M6	76,85 %
11	75,08 %
TRIPL	66,38 %

Total overview of phases combined

Machine	(%)GAP	TB+TS (%)	Utilization	TS(%)
27	53,34 %	0,00 %	100,00 %	0,00 %
29	75,78 %	0,00 %	100,00 %	0,00 %
FSW4	94,08 %	0,23 %	99,75 %	0,23 %
HLNLB	85,68 %	0,00 %	99,61 %	0,00 %
ART	18,55 %	1,77 %	98,00 %	0,95 %
ORION	25,40 %	0,80 %	97,84 %	0,60 %
KAL3	73,79 %	2,82 %	96,63 %	0,00 %
KAL4	13,98 %	3,66 %	96,16 %	0,00 %
97	77,12 %	3,11 %	95,89 %	3,08 %
53	6,50 %	4,50 %	95,16 %	3,26 %
98	73,90 %	4,17 %	95,09 %	4,00 %
55	7,57 %	5,88 %	93,58 %	1,99 %
96	67,23 %	5,71 %	93,20 %	5,57 %
BIAS7	35,35 %	1,78 %	92,85 %	0,02 %
LTM	7,97 %	8,05 %	91,95 %	7,27 %
99	72,94 %	7,34 %	91,54 %	7,04 %
BIAS5	41,84 %	0,64 %	91,07 %	0,06 %
PASM1	35,08 %	6,65 %	89,36 %	6,46 %
Agri Press	9,30 %	11,23 %	88,77 %	11,23 %
45	10,09 %	6,66 %	88,39 %	6,65 %
43	11,24 %	7,53 %	86,98 %	7,01 %
M4	13,75 %	13,37 %	86,63 %	0,29 %
51	0,29 %	12,19 %	84,77 %	3,14 %
M5	13,02 %	15,65 %	84,35 %	0,18 %
47	9,45 %	10,84 %	84,05 %	9,71 %
9	9,57 %	8,82 %	83,68 %	7,65 %
41	10,09 %	11,66 %	82,20 %	8,22 %
49	9,47 %	13,02 %	81,12 %	7,64 %
TINCH	11,25 %	8,97 %	80,04 %	0,32 %
M8	7,11 %	20,40 %	79,60 %	0,05 %
7	7,78 %	16,37 %	77,71 %	10,12 %
M6	11,42 %	23,15 %	76,85 %	0,17 %
11	12,85 %	19,35 %	75,08 %	9,70 %
TRIPL	14,56 %	33,59 %	66,38 %	0,00 %

Figure A- 3: *Dashboard page 1 “Bottleneck identification” – tables for Phase 1-3.*



Curing LB

DownDescr	Min	Machine	Department	Line
GGB	76080	209	Curing	LB
GGB	63527	211	Curing	LB
Total	**786069**			

Curing SM

DownDescr	Min	Machine	Department	Line
GGB	37564	153A	Curing	SM
Total	**895149**			

Components

DownDescr	Min	Machine	Department
ART Geen hieldraad	25	ART	Components
MNTL Geen mantelmateriaal	5989	ART	Components
SPM8 Geen rubber	30	ART	Components
Kraan defect	1170	BIAS5	Components
Reknr. niet op voorraad	375	BIAS5	Components
Kraan defekt	229	BIAS7	Components
Reknr. niet op voorraad	502	BIAS7	Components
Kraan defect	90	CALEM	Components
SPM8 Geen rubber	170	FSW4	Components
Geen gevormde hielen	60	HLNLB	Components
MNTL Geen mantelmateriaal	1200	HLNLB	Components
Geen rubber 728	420	KAL3	Components
Geen Rubber	1956	KAL4	Components
Geen chemicalien	295	M4	Components
Geen KCD chemicalien	1790	M4	Components
stop ivm geen voormengsel	1261	M4	Components
Geen chemicalien	172	M5	Components
Geen KCD chemicalien	1671	M5	Components
stop ivm geen voormengsel	989	M5	Components
Geen chemicalien	350	M6	Components
Geen KCD chemicalien	1404	M6	Components
stop ivm geen voormengsel	10	M6	Components
Geen chemicalien	70	M8	Components
Total	**58097**		

Building LB

DownDescr	Min	Machine	Department	Line
Geen Zijkanten	5367	51	Building	LB
Geen Zijkanten	7233	53	Building	LB
Geen Zijkanten	5412	55	Building	LB
Geen voering	3391	51	Building	LB
Geen voering	3742	53	Building	LB
Geen voering	510	55	Building	LB
Geen Schaafstroken	1368	51	Building	LB
Geen Schaafstroken	1345	53	Building	LB
Geen Schaafstroken	1175	55	Building	LB
Geen Rubber	60	55	Building	LB
Geen Rubber	900	96	Building	LB
Geen Rubber	870	97	Building	LB
Geen Rubber	1170	98	Building	LB
Geen Rubber	870	99	Building	LB
Geen RC stroken	120	51	Building	LB
Geen RC stroken	160	53	Building	LB
Geen RC stroken	990	55	Building	LB
Geen Ply	4354	51	Building	LB
Geen Ply	4096	53	Building	LB
Geen Ply	4100	55	Building	LB
Geen Loopvlak	120	51	Building	LB
Geen Loopvlak	170	97	Building	LB
Geen Karkassen	25689	96	Building	LB
Total	**225949**			

Building SM

DownDescr	Min	Machine	Department	Line
Geen Gordels/Brekers	6421	11	Building	SM
Geen Hielen	12890	11	Building	SM
Geen Loopvlak	14558	11	Building	SM
Geen PA materiaal	2810	11	Building	SM
Geen Ply	2597	11	Building	SM
Geen Gordels/Brekers	895	27	Building	SM
Geen Hielen	12652	27	Building	SM
Geen Loopvlak	6674	27	Building	SM
Geen PA materiaal	2835	27	Building	SM
Geen Ply	1226	27	Building	SM
Geen Gordels/Brekers	1703	41	Building	SM
Geen Hielen	15431	41	Building	SM
Geen Loopvlak	6064	41	Building	SM
Geen PA materiaal	3550	41	Building	SM
Geen Ply	2308	41	Building	SM
Geen Gordels/Brekers	889	43	Building	SM
Geen Hielen	17071	43	Building	SM
Geen Loopvlak	6242	43	Building	SM
Geen PA materiaal	3252	43	Building	SM
Geen Ply	972	43	Building	SM
Geen Gordels/Brekers	979	45	Building	SM
Geen Hielen	13837	45	Building	SM
Geen Loopvlak	6654	45	Building	SM
Total	**288891**			

***Figure A- 4:** Dashboard page 4 “Information starvation” – Starvation description per machine.*

***Figure A- 5:** Dashboard page 5 “Machine Information” – Overview of the bottleneck machine over time.*

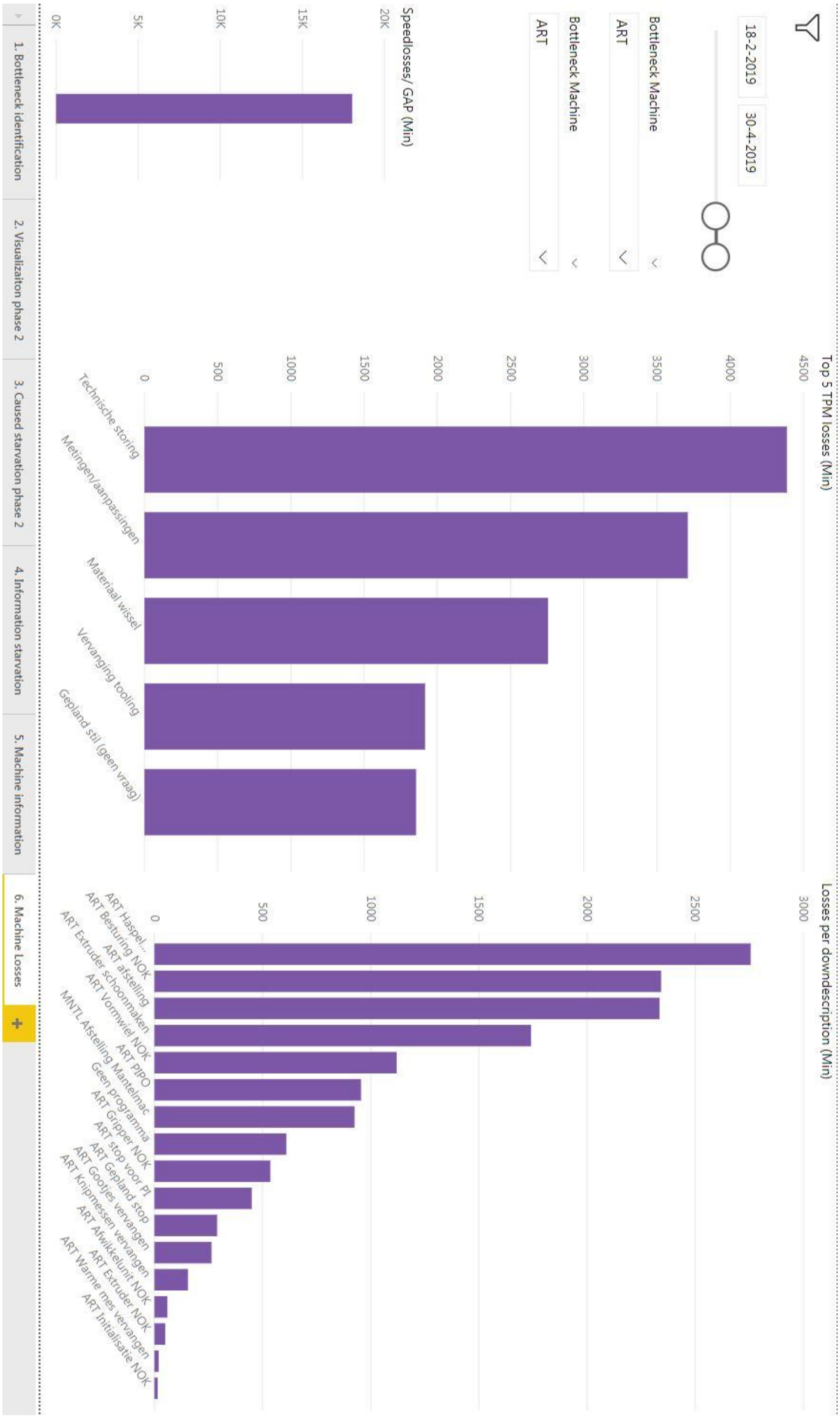


Figure A- 6: *Dashboard page 6 “Machine losses” – The top losses at the bottleneck machine.*

Appendix 3: Extensive descriptions of causes

1. The PIPO (Periodiek Inspectie Preventief Onderhoud) is planned far ahead. This means that the PIPO can be scheduled in a time period that has an extraordinarily high workload. The PIPO is planned far ahead because the schedule includes the entire plant. The impact of the PIPO for the ART varies, because the load of the ART is irregular. There is only a small buffer (safety lead time) to limit the impact, which makes the timing of the PIPO for the ART very important.
2. Rush orders can cause additional changeover times. These rush orders occur because of last-minute changes in demand or because the demand is not present in the planning. Last-minute changes can occur in three situations. First, if planning is not followed, too many or too few tyres for an order are made. Too few tyres affect the succeeding processes and too many tyres affect the preceding processes. That means, if the building department produces too many tyres for one order, they are using input materials that are not linked to that order and thus reserved for another order. When that order needs to be produced, the material is not available and this will result in a rush order. Second, a certain amount of greentyres is rejected and becomes scrap. In the planning they estimate the amount of scrap, but in reality the amount of scrap fluctuates. That means that the amount of greentyres produced is not sufficient to fulfil the demand from the curing department. Depending on the order, a decision is made to place a rush order to complete the order or to accept the loss at the curing department. Third, the operators at the building department have a different level of skill, which results in different building speeds. The planning uses a fixed speed for everyone. Thus, operators can be faster than what is anticipated in the planning. If the difference is big enough, it can occur that materials for the next order are not available yet. Again, a decision is made to place a rush order to obtain the materials or to accept temporarily not being able to produce. The sub-causes of different levels of skill of operators is described in cause 7. Demand that is not present in the planning is caused by mistakes in the manual assessment of the inventory. The impact of the rush orders is larger, because there is only a small buffer of beads (based on the safety lead time) to deliver from.
3. The planning at the ART consists of small batches because they are linked to an order. The planning manually combines orders if they think it is beneficial. Not only the finished bead is linked to the order, but also the formed beads (without wrapping material) are already linked to the order. Thus, the beads are made to order, which results in small batches.
4. The ART deals with an irregular load. Thus, the demand at the ART is fluctuating. A part of this fluctuation is caused by fluctuations in demand for tyre types throughout the year. Another part is caused by the division of agricultural beads specs on the ART and HVM4. The planning department does not take this division into account while making the planning. Thus, it can occur that one week most agricultural bead specs need to be produced on the ART and the other week on the HVM4. This difference has a large impact on the load of the ART.
5. The ART is a non-automatic machine. This means that a lot of the work is done manually and requires a lot of time. This is caused by the machine being very old. This is a condition that the process needs to deal with.
6. There is a large number of different bead specs resulting in many changeovers at the ART. Vredestein offers a great variety of tyre types per product line, which increases the complexity of the plant. This is one of the unique selling points of the plant and is also a

condition that the process needs to deal with. Also, all SM tyres and a part of the AGRI tyres can only be processed on this machine. This means that the machine not only deals with different tyre types within one product line, but within two. This increases the number of specs.

7. The level of skill between operators can vary greatly. This impacts not only the working speed, but also the way of working and dealing with defects. This is further described in cause 8. The different levels of skill are mainly caused by the amount of training that operators have had on the machine. Of course, the natural ability of an operator also contributes to the level of skill. There is a great deviation in the amount of training, because we work with temporary workers in addition to the permanent employees. Also, sometimes employees from other machines or departments are used to support areas with a higher workload.
8. Sometimes major failures occur at the engine. Often these defects occur as a result of small defects not being noticed. An example includes the wire cutter. A small defect at the wire cutter resulted in the wire not being completely cut through. Thus, the wire is teared loose by the machine. Every time this happens, the engine must deliver more torque. After some time, this results in a major failure at the engine. Skilled operators notice these defects. In this case they notice the sound that is created by tearing the wire. Operators with a low level of skills do not notice smaller defects that, in time, cause the major failures.
9. It is inevitable that the machine needs some preventive calibration. However, a lot of time is lost with calibrations that can be prevented because they are a machine failure. Due to a bug in the software, the wire cutter sometimes stops. After the bead is pulled down manually, the wire cutter is not automatically activated. The machine needs to be calibrated to activate the wire cutter.
10. A lot of time is spent fine-tuning the ART. Every operator starts his shift with fine-tuning the machine according to his knowledge. This has two sub-causes: the possibility to fine-tune and not having a standardized procedure. It is unclear what should be fine-tuned and what the setting should be. This results in a different opinion per operator and thus continuous fine-tuning between shifts.
11. The beads are formed around a shaping wheel. The beads of size 18 inch 16 strings need to be removed manually from the shaping wheel, because the shaping form does not fold in correctly. The shaping form does not fold in correctly, because the gripper does not grab this size.
12. Uneven rubberization of steel wires. Uneven rubberization is caused by a clogged extruder. The longer a clogged extruder stays unnoticed, the higher the impact. The camera placed after the extruder is broken, which hinders the detection of uneven rubberization. Also, uneven rubberization occurs more often at high speeds. A clogged extruder can be caused by two things: low quality rubber or overdue cleaning. A low quality rubber pollutes the extruder faster.
13. New safety issues are tackled throughout the factory. For the ART this led to temporary safety locks. The temporary safety locks take more time compared to permanent safety locks.
14. A spool of steel wire is replaced by hand. They used to do this with a carriage, but the carriage is defect. The advantage of the carriage is that it can be prepared before replacing

the spools. Thus, the time to replace the wire and thus the time the machine stands still is a little less with a carriage.

15. There are many defects expected to be caused by insufficient periodic maintenance. This is caused by unclear relations between defects and responsibilities. There are two parties involved with defects: the shift mechanic and technical service (day shift). They often point to each other as the responsible person of that defect. This is caused by unclear division of tasks.
16. There is a variation in rubber adhesion to the steel wire, because they use different qualities of steel wire. The different qualities of wire come from three different suppliers.
17. No wrapping material in stock means that they cannot produce beads. A shortage of wrapping material is caused by fluctuations. There are five situations that can cause fluctuations. First, the rolls can contain different lengths of material, but there is always an entire roll booked in the system. I.e. rolls that have the same SKU code can differ in size. Also, no matter the size, an entire roll is booked in the system. Therefore, while there is enough stock present in the inventory system, it might not be enough in practice. This leads to material shortages. The material is order related meaning that all material booked in the system is needed. The difference exists because the length of the roll (from the ORION) is not booked. The length is mostly defined two processes prior, at KAL4. After KAL4 the “mother roll” is cut at succeeding processes with a minimum amount of scrap and arrives as wrapping material at the ART. None of these processes book the length of the roll. Second, shortages can also occur when the production planning is not followed. This can be for both the delivering and demanding process. If the delivering process does not follow planning, delivery deadlines can be missed causing shortages. If the demanding process does not follow planning, it is using material that is not accounted for. Thus, it is using material meant for another order, which leads to shortages later on. The main reason for not following planning is the KPIs that are used. Currently they steer on numbers produced, which means that for instance postponing a set up to the next shift by producing more than planned is beneficial for their KPIs. Third, the irregular demand at the ART causes overcapacity sometimes, and under capacity at other times. If there is overcapacity they can build up stock. This stock can grow over 8 hours, but the planning horizon does not go further than 8 hours. Even though they have no plan, they continue producing, because they know the situation can easily shift. Thus, they start making beads with regular demand. These production batches are discussed with the planning department and orders needed for input materials are created. Because the ORION is also a machine with a high utilization and these orders are added last-minute, the material often arrives too late, causing shortages. Note that these shortages are only occurring if the machine is ahead of schedule and thus not the most significant bottleneck at that point in time. Fourth, large defects at the ORION result in shortages for its succeeding processes. This can also result in not delivering wrapping material in time at the ART. Fifth, fluctuations that occur are not absorbed enough. The current buffer is not sufficient to deliver from in case of unexpected changes, such as fluctuations.

Appendix 4A: Probability-Impact Matrix Form

Wat is de invloed van onderstaande punten op de productie aantallen van de ART?

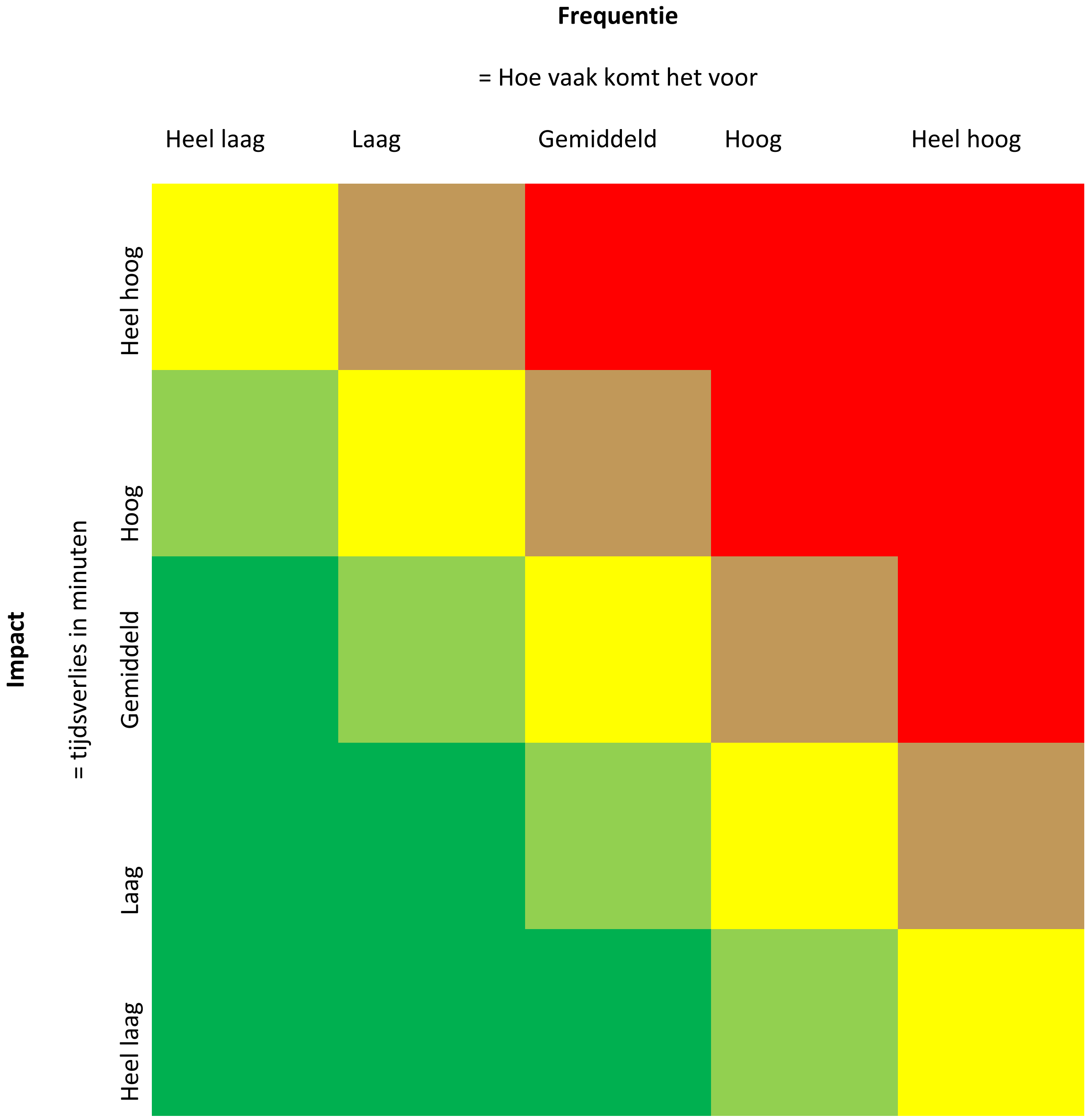
Deze punten vergelijken we op twee aspecten: **impact = tijdsverlies per keer dat het voorkomt** en **frequentie = hoe vaak het voorkomt.**

Deel de punten in op het schema op de volgende pagina. Dit kun je doen door het bijbehorende nummer in te vullen in een van de 25 gekleurde vakken waar deze naar jouw mening thuishoort. Er mogen meerdere punten in 1 hokje geplaatst worden.

Voorbeeld: Als je een 1 invult in het gele hokje links bovenin, dan betekent dat dat "Pipo op ongewenste momenten" heel weinig voorkomt en als het voorkomt heel veel minuten tijdsverlies veroorzaakt.

Invloeden op de productie aantallen van de ART:

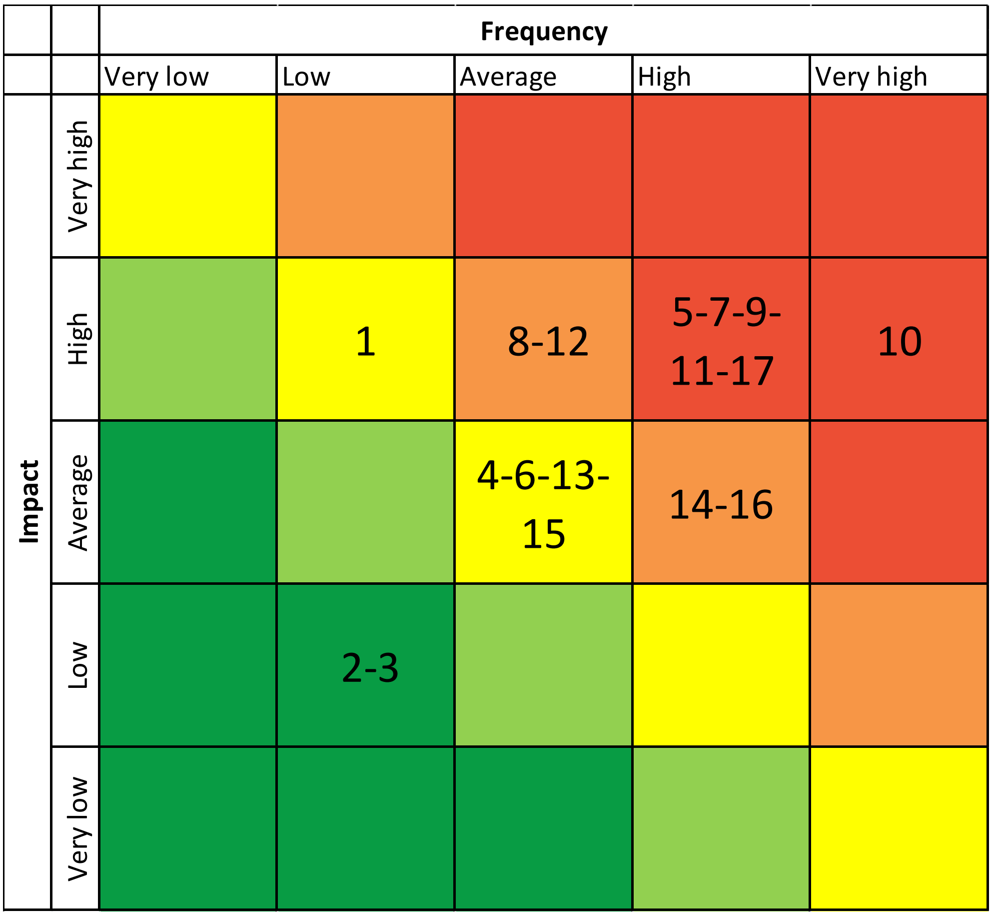
1. Pipo op ongewenste momenten
2. Spoed orders
3. Kleine orders in schema planning
4. Onregelmatige belasting ART
5. Oude machine waar veel met de hand moet gebeuren
6. Groot aantal specificaties hielen
7. Verschil in niveau van de operators
8. Storingen bij de motor
9. Extra kalibreren (Soms stop het knipmes en gaat het knipmes niet vanzelf aan nadat de hiel er met de hand afgehaald is)
10. Veel afstellen van de machine
11. Vormwiel klapt bij sommige LB hielen niet goed in
12. Onregelmatige berubbering staaldraad
13. Tijdelijke veiligheidsslotjes kosten extra tijd
14. Staaldraad wordt met de hand vervangen
15. Onvoldoende periodiek onderhoud
16. Wisselende hechting van rubber aan het staaldraad
17. Mantelmateriaal niet op voorraad



Als deze is ingevuld, graag opsturen naar: **XX@XX.com**

Er zal vertrouwelijk met deze informatie worden omgegaan.

Appendix 4B: Average Probability-Impact Matrix



		Frequency				
		Very low	Low	Average	High	Very high
Impact	Very high					
	High		1	8-12	5-7-9-11-17	10
	Average			4-6-13-15	14-16	
	Low		2-3			
	Very low					

Appendix 5: Template for rolls of wrapping material

A template to identify rolls of wrapping material that are smaller than 176 m (to be printed true to size).