BACHELOR THESIS

Improving the Green Tyre Inventory of Space Master at Apollo Vredestein B.V.

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UNIVERSITY OF TWENTE.

apollo TYRES

VREDESTEIN

This report is intended for Apollo Vredestein B.V. and the examiners from the University of Twente.

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Improving the Green Tyre Inventory of Space Master at Apollo Vredestein B.V.

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Preface

Dear reader,

In front of you, my bachelor thesis 'Improving the Green Tyre Inventory of Space Master at Apollo Vredestein B.V.'. This report was written for the purpose of graduating from my bachelor Industrial Engineering and Management at the University of Twente. I conducted this research from February until July 2020 at the industrial engineering department of Apollo Vredestein B.V. During these months, I gained a lot of insights into the application of theory in practice and the industrial engineering profession.

I would like to thank Apollo Vredestein for giving me the opportunity to perform my thesis under their guidance. During my research, I always felt welcome and part of the team, even in the strange times of Covid-19 and the announced reorganisation. More specifically, I want to thank the industrial engineering department and the coordinators of the space master production line, for always willing to help me and for providing me with the necessary information. In particular, I want to thank Ron Peeks, who always found the time to think along and to provide me with helpful feedback, despite his busy schedule.

Furthermore, I would like to thank Engin Topan for his guidance and useful feedback to bring this research to a higher level.

Finally, I would like to thank my friends and family for their support and genuine interest. I appreciate your involvement in any form.

I hope you enjoy reading my bachelor thesis!

Susanne Heesterman

Enschede, July 2020

Management Summary

We perform this research at Apollo Vredestein B.V. as part of the bachelor thesis of the Industrial Engineering and Management educational program at the University of Twente.

Problem description

The target output of Space Master tyres are currently not reached. Apollo Vredestein wants to increase the output by increasing systemwide throughput according to the methodology Theory of Constraints. Accordingly, the curing department has been identified as the bottleneck. To improve systemwide throughput, the utilization of the curing presses should be maximized by increasing the green tyre availability. The current green tyre availability is $< 98\%$, while the target is $\geq 98\%$. Therefore, Apollo Vredestein has asked to realize a part of the exploitation of the bottleneck by asking the following question:

“How can we manage the green tyre inventory in the building phase of Space Master to improve green tyre availability in line with the Theory of Constraints?”

We arranged meetings with employees of Apollo Vredestein and identified the following core problem based on the retrieved information:

‘There are no KPIs defined in the building phase to monitor and control the green tyre inventory of the curing phase to improve green tyre availability.’

Therefore, to solve this problem and to answer the main research question, we have to research two aspects, inventory control and KPI implementation.

Inventory control

To determine how we can manage inventory, we research how we can monitor and control inventory. We define inventory control objectives and compare inventory control policies. We identify an (R, s, Q) inventory control policy as the most suitable for the green tyre inventory because it has periodic review and we can order a multiple of the fixed order quantity. We decide to review the inventory every shift. When the inventory position is below reorder level s, a multiple of the determined order quantity of 102 green tyres will be ordered. There are no demand uncertainties, so to buffer against supply uncertainties a safety lead time is introduced. A safety lead time is in line with the buffer definition of the Theory of Constraints. The safety lead time is included in the reorder level, such that the necessary green tyres are available in inventory before they have to be cured. Currently, it is not possible within the system to implement a safety lead time per SKU, so a weighted average based on demand between the 1st of January 2019 and the 31st of January 2020 is determined. This gives a safety lead time of 3.14 hours. The introduction of this safety lead time results in a product availability of $\geq 98\%$, based on historical data, see Figure 1.

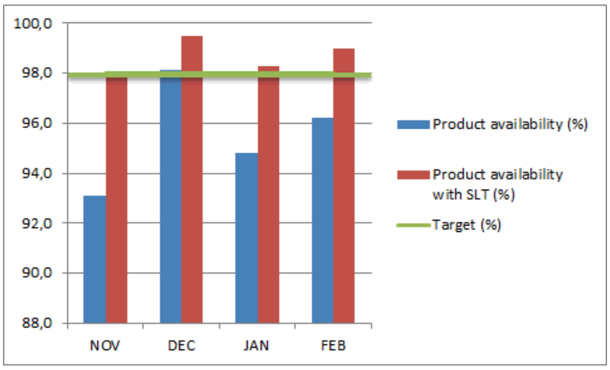

Figure 1 Product availability

KPI implementation

Next, to improve green tyre availability we implement a KPI to monitor and control the green tyre inventory. We interviewed stakeholders for their objectives and criteria. Based on these criteria, we find that the KPI should effectively represent its goal 'insight in qualitative inventory'. We list KPIs related to inventory monitoring and control on an operational level. We define a KPI as effective when it suffices the criteria importance, ease and actionable. We research the optimum number of KPIs, KPI selection methods and how to effectively visualize KPIs. We identify AHP as the most suitable KPI selection method. We base our method on the proposed method of Shahin & Mahbod (2007), combining AHP with the criteria importance, ease and actionable. A survey is conducted with the end-users of the KPI to compare the criteria and KPIs pairwise. Based on this result, we select stock cover with a minimum and maximum inventory level as KPI. Next, we identify a progress bar as the most suitable visualization method because it can indicate the progress of the inventory compared to the target levels. We visualize the target levels with the three colours of the traffic light, see Figure 2. The minimum level chosen is the safety lead time identified from the (R, s, Q) policy, which is coloured red. Based on the review period of one shift, the intermediate level is the demand of one shift and the maximum level is the safety lead time of the succeeding shift. The intermediate level is coloured orange and the maximum level is coloured green. We check if we suffice all objectives and criteria of the stakeholders. We miss one insight, the number of employees in the building and curing phase planned in succeeding shifts, which we include as supporting analytic. We validated the effectiveness with the end-users, which graded the effectiveness of the KPI with an 8.8. We implemented both the KPI and supporting analytic in the daily report of Space Master tyres.

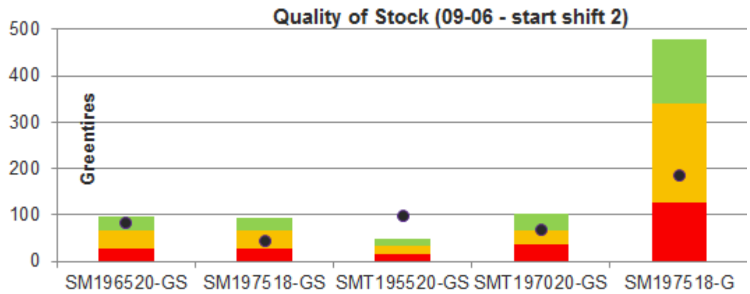

Figure 2 Implemented KPI

Conclusions and recommendations

We conclude that we can manage the green tyre inventory in line with the Theory of Constraints by inventory control and KPI implementation. The implementation of the (R, s, Q) inventory control policy with R = one shift, Q* = 102 green tyres and the reorder level determined per SKU improves the green tyre availability such that it is ≥ 98%. Next, the implementation of the KPI stock cover including a minimum and maximum inventory level positively influences the green tyre availability. The users validated that they can effectively steer with this KPI on the green tyre availability. Therefore, we recommend to implement the (R, s, Q) inventory control policy and to use the implemented KPI stock cover with a minimum and maximum inventory level and supporting analytic '*Number employees in the building and curing phase planned in succeeding shifts*'. Next, we recommend further research to maximize the utilization of the curing presses. We suggest to research the other two core problems which we can influence, namely adjusted production norms for the building phase and the unaccountable downtime of the curing phase.

Table of Contents

Table of Figures

Glossary

Abbreviation	Meaning
AGRI	Agricultural tyre
AHP	Analytic Hierarchy Process
BOM	Bill Of Materials
CS	Cycle Inventory
CSL	Cycle Service Level
EPQ	Economic Production Quantity
GT	Green Tyre
KPI	Key Performance Indicator
MCDA	Multiple-Criteria Decision Analysis
MPS	Master Production Schedule
MPSM	Managerial Problem-Solving Method
MRP	Material Requirements Planning
NGT	No Green Tyre
PCT	Passenger Car Tyre
PIBS	Production Information Control System
Q	Order quantity
R	Review period
s	Reorder level
S	Order up to level
SIPOC	Supplier, Input, Process, Output, Customer
SKUs	Stock keeping units
SLT	Safety Lead time
SM	Space Master tyre
SS	Safety Inventory
TOC	Theory of Constraints
W	Total available storage space
z	Safety factor

1. Introduction

In this chapter, we introduce the context of the research. In Section 1.1 we introduce the company the research is conducted for, namely Apollo Vredestein B.V. In Section 1.2, we elaborate on Space Master tyres. Next, in Section 1.3 we describe the research motivation, followed by the research design in Section 1.4. We identify the problem in Section 1.5 and formulate the research approach in Section 1.6. Next, we explain the research scope in Section 1.7 and the deliverables in Section 1.8.

1.1 About Apollo Vredestein B.V.

Vredestein was found in the Netherlands in 1909 by Emile Louis Constant Schiff. Being one of the oldest car tyre manufacturers of the world, it is a major player in the global industry of car tyres. They develop, produce and sell first-class tyres and have achieved a premium brand status. The company name changed to Apollo Vredestein B.V. after being acquired in 2009 by the largest tyre producer of India, Apollo Tyres Ltd. Today the firm sells both brands, Apollo and Vredestein, of high-quality tires in Europe, but is also available in more than 100 other countries in the world (Apollo Tyres Ltd., 2020).

The headquarter of Apollo Vredestein B.V. is based in Amsterdam and their production plants are found in The Netherlands, Hungary and India. They produce passenger car tyres (PCT), space master tyres (SM) and agricultural tyres (AGRI), shown in respectively Figure 3, 4 and 5. Within these three specializations, there is a lot of variety regarding width, height, inch and material, resulting in a lot of stock-keeping units (SKUs).

Figure 5 Passenger Car tyre

Figure 4 Inflated and uninflated Space Master tyre

Figure 3 Agricultural tyre

Although there are specializations and variations, all tyres undergo a comparable production process. This general production process is shown in Figure 6.

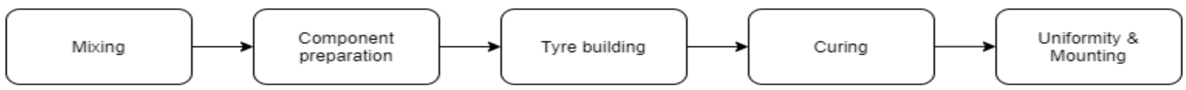

Figure 6 General production process of a tyre

1.2 Space Master tyres

As the research motivation is focused on space master tyres only, we first provide some context regarding these tyres. A space master tyre is an inflatable spare tyre. It is a unique product of Apollo Vredestein and accounts for 8% of the annual turnover (Apollo Vredestein B.V., 2011). The tyre realizes a space reduction up to 60% and a weight reduction up to 35%, but when inflated it has the same diameter as the original wheel (Vredestein Banden, 2011). The tyre structure is somewhat different from a regular tyre to realize those reductions. It is composed of the components shown in Figure 7.

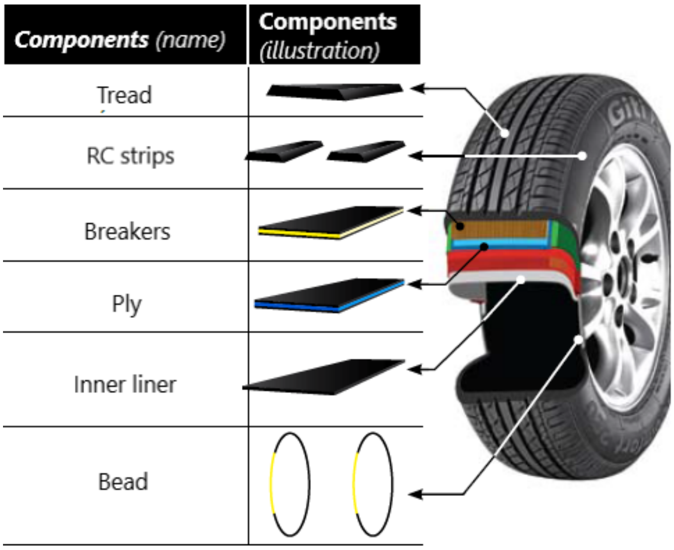

Figure 7 Tyre structure. Adapted from "The Unofficial Global Manufacturing Trainee Survival Book", (Apollo Vredestein B.V., 2015)

In total are there 25 SKUs of space master differing in height, width, inch and if it has an extra silica layer on the thread. The SKU names are based on those differences. For example, SKU SM195520-GS has a tread height of 195 mm, a width of 55% of his height and a diameter of 20 inches. GS stands for Green tyre Silica and indicates the last potential difference between SKUs. Namely, that an extra layer of silica is applied to the thread.

1.3 Research motivation

At the moment Apollo Vredestein has a monopoly position on the market regarding SM tyres. However, the current demand is not met, because the target output is not reached within the production line. Apollo Vredestein wants to reach the target output by an increase in systemwide throughput, by following the methodology Theory of Constraints (TOC). Currently, TOC is already introduced in the production line of PCT. The goal is to introduce this in the production line of SM as well. Some steps to introduce TOC in SM are the same as in PCT. Therefore, we first elaborate on the Theory of Constraints before we state the research question from Apollo Vredestein.

1.3.1 Theory of Constraints

The Theory of Constraints is a methodology for continuous improvement introduced by Goldratt. He describes in his book 'The Goal' (Goldratt & Cox, 1986) that every system has at least one constraint, known as the bottleneck, determining the performance of the system. The capacity of the system is limited by the capacity of the bottleneck and can only be increased if the capacity of the bottleneck is increased (LeanProduction, n.d.). The theory, therefore, stresses to identify the bottleneck and maximize its utilization. This is done according to the 'Five Focusing Steps' (Goldratt, 1990):

1. Identify the System's Constraints.
2. Decide How to Exploit the System's Constraints.
3. Subordinate Everything Else to the Above Decision.
4. Elevate the System's Constraints.
5. If in the Previous Steps a Constraint Has Been Broken, Go Back to Step 1.

The performance of the company can be measured according to TOC by the throughput, inventory and operational expenses (Rattner, 2006). Throughput is defined as the revenue generated by the system through the production of sold products. Next, inventory is defined as any cost incurred for items retained in the organization. In other words, it is all the money invested in products intended to sell (Rattner, 2006). Finally, operational expenses are defined as all costs incurred to turn inventory in throughput (Rattner, 2006). They are all treated as period expenses, which must be covered by the throughput the system generates. The performance can only be improved by increasing the throughput, decreasing the inventory or decreasing the operational expenses. By optimizing those three operational measures, the system will be optimized (Sheu, Chen, & Kovar, 2003).

1.3.2 Research question

Not reaching the target output is an internal constraint according to TOC (Landau, 2018). Step 1 and 2 of the 'Five Focusing Steps' are the same for PCT and SM. Therefore, Apollo Vredestein identified these two steps for SM the following:

1. **Identify the System's Constraints.**
   The production line of SM tyres consists of several steps, from which the second-last is curing. Curing is the first step in the process where the product becomes specific and thus where demand and planning converge. Therefore, the production planning is made according to the curing capacity and thus is curing identified as the bottleneck. More information about the production planning can be found in Section 2.2.

2. **Decide How to Exploit the System's Constraints.**
   The input of the curing phase is a complete green tyre, the output of the building phase. With 25 SKUs, there is a variation of tyres within the SM line itself, see Section 1.2. For every green tyre SKU, a different mould is used in the curing press. As it takes a significant time to change the mould in the curing press, it is of high importance that the right inventory is available. With this knowledge, Apollo Vredestein decided that a suitable buffer is needed to maximize the utilization of the curing presses. This buffer should represent the amount of time that the green tyres should arrive in advance of being used (LeanProduction, n.d.).

Apollo Vredestein measures the utilization of the curing presses accordingly, namely the idle time because there is no matching inventory available. This percentage is used to steer and known within the company as No Green Tyre (NGT). Unfortunately, this percentage is above their target value of two percent as shown in Figure 8. Therefore, Apollo Vredestein asked to realize a part of the exploitation of the bottleneck with the following question:

"How can we manage the green tyre inventory in the building phase of Space Master to improve green tyre availability in line with the Theory of Constraints?"

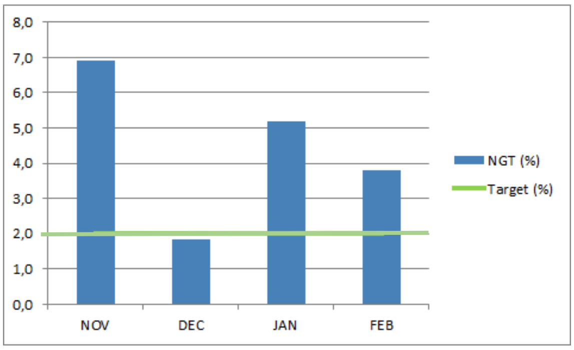

Figure 8 NGT percentage per month relative to the target value

1.4 Research design

The research methodology used for this bachelor thesis is the Managerial Problem-Solving Method (MPSM). This methodology is used for complex practical problems, where investigating and troubleshooting meet (Heerkens & van Winden, 2017). We are dealing with the practical problem of not having the right inventory at the right moment, influenced by a lot of factors making it complex and which should be investigated to troubleshoot and find a solution. That makes it clear that MPSM is a very suitable methodology for this research. The methodology is divided into the following seven phases:

1. Problem identification
2. Formulating the approach
3. Analyzing the problem and current system
4. Formulating alternative solutions
5. Choosing a solution design
6. Implementing the solution
7. Evaluating the solution

From now on, the research is structured according to those phases. In Section 1.5, we identify the problem. In Section 1.6, we formulate the research approach per chapter. Next, in Chapter 2 we analyze the problem and the current system. In Chapter 3, we formulate alternative solutions by conducting a literature review. Then, in Chapter 4 we choose a solution design. In Chapter 5, we implement the solution and finally, the conclusions and evaluations are discussed in Chapter 6.

1.5 Problem identification

We identify the core problem by reasoning from the management problem, being that the target output of Space Master is not met, to find potential core problems. We do this by arranging meetings with employees of Apollo Vredestein. Based on the retrieved information, we make a problem cluster, see Figure 9, and choose a core problem based on rules of Heerkens & van Winden (2017).

Causes of unreached target output

The management problem is that the target output of SM tyres is not reached(1). This has two causes, the first one being that the process steps in the production line take too long(3). The main reason for this is that a lot of knowledge is lost from experienced employees(4), as Apollo Vredestein had to downscale their production(5). This was done because demand had decreased, while now the demand increased again.

The other cause is that there is too much idle time during the curing phase(2). This phase is dealt with like it is the bottleneck and therefore it was chosen to exploit the constraint by reducing the idle time. This can be managed at two levels, namely the curing performance(6) and NGT percentage(10), the idle time because there is no suitable green tyre available. The curing performance measures the downtime of the curing presses, not related to the NGT. This performance is too low because there is a lot of downtime(7). The downtime is a result of many technical disruptions(9) and a lot of unaccountable downtime(8). On the other hand, the NGT percentage is too high(10).

Causes of a high NGT

The causes of a high NGT(10) lie in both criteria to calculate the percentage NGT, namely the type of green tyres available and the type of moulds in the curing machine available. Changing the mould to suit the green tyre is expensive(11), because the action itself is time-consuming

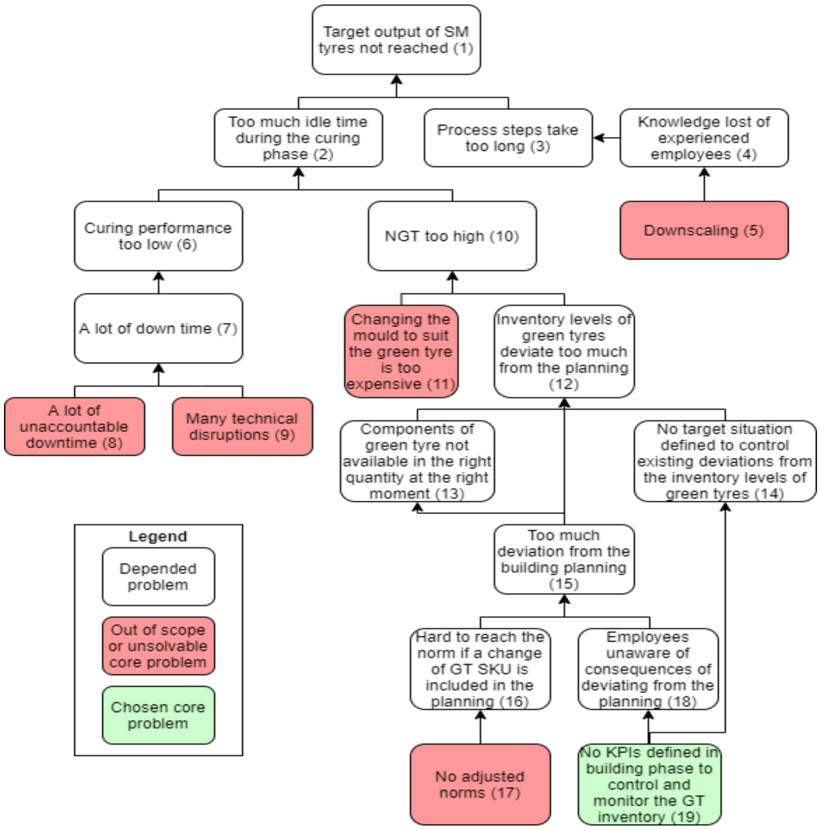

Figure 9 Problem cluster

and warm-up and cleaning time should be included as well. Next to that, the inventory level of green tyres deviates from the planned inventory(12). This has three reasons, beginning with the fact that there are no target inventory levels defined for the coordinators to control deviations(14). If coordinators are not aware that the inventory levels deviate, they cannot manage the building phase to minimize those deviations. This can be done by letting the most experienced builder, for example, build the green tyre with the relative lowest inventory. There is no target situation defined because there are no KPIs defined in the building phase to monitor and control the green tyre inventory(19). KPIs measure a company's success versus a set of targets (Twin, 2019), so the determination of the target situation is part of KPI determination.

Another reason is that there is too much deviation from the building planning(15), resulting in an inventory level differing from the planning(12). While deviating, builders sometimes take a component they are missing to build another green tyre from a colleague. This, of course, causes that the components of the green tyre from this colleague are not available in the right quantity at the right moment(13). When this is the case, a green tyre cannot be built and thus will the inventory level deviate from the planned inventory level(15).

A reason for deviating from the planning is that the builders have a norm of tyres which they have to reach at the end of their eight-hour shift. This norm is hard to reach according to the builders if they have to change to another type of tyre(16). The machine has to be rebuilt for this, which takes time. Being eager to reach the norm, sometimes builders decide to deviate from the planning and not build a different type of tyre. The cause of this is that there are no adjusted norms(17). A lower norm if a tyre change is included, will reduce the pressure to deviate.

Next to that, the builders and coordinators are not aware of the consequences of deviating from the planning(18). If one does not know the importance of working according to the planning and the effects of deviating, one will not be withheld to deviate. They are not aware of this, because there are no KPIs defined to monitor and control the green tyre inventory(19). KPIs related to the green tyre inventory level can monitor the current situation and at the same time show what the targeted situation is. It can thus show what the effect is on the GT inventory if they deviate.

1.5.1 Core problem

According to Heerkens & Van Winden (2017), core problems are the ones which have no direct cause themselves. Therefore, we are left with six possible core problems, problems 5, 8, 9, 11, 17 &19. The next rule stated is that if you cannot influence something, then it cannot become a core problem. We cannot influence problem 5, as downscaling already has happened and we cannot turn back time. Problem 5 is thus not a core problem we can work with. Another problem we cannot influence is problem 11, as the costs of changing a mould are fixed costs and cannot be made cheaper without any big investments. Therefore, we can also not work with problem 11 as the core problem. This leaves us with four possible core problems, namely problem 8, 9, 17 & 19. In this case, the next rule states that we should choose the most important problem. As this research is part of a bigger project implementing TOC, we should focus on maximization of the utilization and thus the NGT performance. This brings problem 8 & 9 out of scope, resulting in problem 17 & 19 as two potential core problems. Problem 19 is the direct cause of two problems in the problem cluster, while problem 17 is the direct cause of one problem. Next, problem 18 can only be solved by introducing an adjustable norm, which is not in line with the current strategy. Therefore, we identified the following core problem:

‘There are no KPIs defined in the building phase to monitor and control the green tyre inventory of the curing phase to improve green tyre availability.’

Expressed in terms of norm and reality, the reality is that the green tyre SKUs are less than 98% available for curing per shift. The norm is that the green tyre inventory will be monitored and controlled in the building phase such that the green tyre SKUs are more than 98% available for curing each shift, monitored by presenting the current situation and controlled by presenting the targeted situation. Examples of such KPIs can be product availability, service level, inventory levels per SKU, etc.

Product availability is the reverse of the NGT. Both formulas are defined according to Apollo Vredestein (2020) in Formula 1 and 2 respectively. We use both in this research, as NGT is in interest of Apollo Vredestein and product availability is in line with the industrial engineering perspective.

$$Product\ availability\ (\%) = 100\% - NGT\ (\%) \qquad (1)$$

$$NGT\ (\%) = \frac{Down\ time\ because\ there\ are\ no\ green\ tyres}{Total\ available\ time - Planned\ Maintenance} \qquad (2)$$

1.5.2 Relevance

Currently, the defined KPIs motivate to produce a high output. The builders only see the number of green tyre SKUs they have built and the production norm. This information is updated manually by the builders. Unfortunately, those numbers are not presented in relation to the green tyre inventory or demand of the curing presses. Therefore, they cannot monitor the current situation and control, if needed, to become closer to the targeted situation. By defining KPIs that relate to this, coordinators will know what the output of the building phase should be to suffice the throughput of the curing phase and thus how to monitor and control the inventory of curing. They will know how to steer on better product availability, as well as how to control existing deviations to still have sufficient inventory for curing.

1.6 Research approach and research questions

In this section, we describe the research approach based on the phases of the MPSM. Also, we define the research questions per chapter.

Chapter 2: Current system

In this chapter, we analyze the problem and current system, as in phase three of MPSM. This is important because if we want to know how to manage the inventory levels, we first have to know how they are managed now.

1. ***What are the steps of the production process of the Space Master tyres?***
   General knowledge of the production process is required for this research. This helps understanding from which factors the building and curing phase are dependent, as well as to understand the terminology used within the company.

2. ***How is the production planned for the building and curing phase?***
   We want to understand the demand and supply process of the green tyre inventory. This means that we have to understand how the production is planned for the building phase, the supply, and the curing phase, the demand.

3. ***How are the green tyre inventory levels determined?***
   Next, we have to analyze how the green tyre inventory levels are determined currently. This includes how it is defined, how its tracked, how it is regulated and how is steered on it.

4. ***Who are the stakeholders and what are their objectives?***
   We conduct a stakeholder analysis to find out who they are and what their objectives are. Next, we also ask stakeholders what their criteria are for the KPI(s), which we have to take into account when selecting KPIs.

Chapter 3: Literature review

The third chapter focuses on how to formulate alternative solutions, linked to phase four of MPSM. Those are formed by a literature review on two aspects, namely inventory control and KPI implementation.

Inventory control

5. ***How can inventory be controlled in a production process?***
   First, we will discuss what the objectives are of inventory and how inventory can be controlled in a production process. We need this knowledge to decide how we are going to control the green tyre inventory.

KPI implementation

6. ***What KPIs exist to monitor and control inventory?***
   Second, to define KPI(s) to monitor and control inventory, we have to know which KPIs exist. Therefore, we will research this and list our findings.

7. ***When is a KPI effective in a production company?***
   To make sure the KPI implementation is successful, we research which criteria a KPI has to suffice to be effective.

8. ***What number of KPIs is the most effective to implement in the building phase?***
   Next, we have to know how many KPI(s) we are going to define. Therefore, we research how many KPI(s) are the most effective to implement.

9. ***What methods are available to select KPIs?***
   To define KPI(s) in the building phase, a method has to be created to select the KPI(s). Therefore, we research KPI selection methods and propose a method based on this.

10. ***How can the KPI(s) be visualized the most effective in the building phase?***
   Lastly, we research how we can effectively visualize KPIs for a successful implementation.

Chapter 4: Solution design
In this chapter, we determine the solution design based on the obtained knowledge, as described in phase five of MPSM. We will define how to control inventory to increase product availability, which and how many KPIs we will implement and how we will visualize them.

Chapter 5: Implementation
The next chapter is in line with phase six of MPSM and is to implement the solution. We determine the values of the parameters related to the chosen inventory control method and we will visualize the KPI(s). Unfortunately, the performance cannot be validated based on the product availability before and after the implementation. This is because we have limited time. Therefore, we validate with historical data. This will be done based on the NGT which has been experienced as stated in Section 1.3.2 and the NGT which would have been experienced with the proposed inventory control method. Next, the KPI should be validated. As the effect of the KPI on product availability cannot be determined, a positive evaluation of the KPI from the users validates the KPI. The evaluation is positive when the average grade is ≥ 6.

Chapter 6: Conclusion and evaluation
Finally, we evaluate the research by concluding our findings. Next, we give our contributions to practice and theory, and we discuss the limitations and recommendations for further research.

1.7 Research scope

This research focuses on the space master production line. The other production lines will be out of scope as the process is different. Within the SM production line, the research is restricted to the building and curing phase. Meaning that we deal with the output of the building phase, which are the inventory levels of the curing phase. This is because the main improvement should be made within those phases and there is not enough time available to analyze the other phases as well. Other phases will only be referred to, to improve understanding of those two phases. As this research is part of a bigger research implementing TOC, we will exclude everything not related to this. Aspects like marketing and forecast adherence are also not included, as those departments are not located at the plant in Enschede. The green tyre SKUs to be cured is thus determined based on the demand forecast and will not be treated as a variable.

1.8 Deliverables

- **Selection of KPI(s) including visualization**
  The KPI(s) to monitor and control the green tyre inventory should be selected. The KPI(s) are necessary to steer on the inventory. Next, the logical step is that they will be visualized. This does not mean an entire dashboard, as it presents only a small part of the entire system.

- **Report advising how to manage the green tyre inventory levels**
  The report should advise how to improve product availability through inventory control. The parameters of inventory control should be used as input for the KPI visualization.

2. Current system

This chapter relates to the first four research questions and describes the current system. We elaborate on the production process of SM in Section 2.1, the production planning of SM in Section 2.2 and the determination of the green tyre inventory of SM in Section 2.3. Finally, in Section 2.4 a stakeholder analysis has been conducted including their objectives regarding the KPI implementation.

2.1 Production process

The general production process of a tyre consists out of five stages as stated in Section 1.1. Those stages are mixing, component preparation, tyre building, curing and uniformity & mounting. Based on those stages, we discuss the production process of Space Master tyres in this section, as described in “The Unofficial Global Manufacturing Trainee survival Book” (Apollo Vredestein B.V., 2015) and “Het Productieproces” (Apollo Vredestein B.V., n.d.).

Mixing

The production process starts with the mixing of raw materials, which are categorized into rubbers, chemicals and fillers. The rubber used is a mixture of natural rubber, synthetic rubber made of petroleum and regenerate made of recycled material. The chemicals used influence the characteristics of the rubber to make the production process possible and faster. Fillers are included to improve the wear of the rubber.

The mixing is generally speaking executed in two steps. First, a premixture is created, including all raw materials except the chemicals sulfur, accelerators and incubators. Those are added in the second mixture step, as their chemical reactions would cause the raw materials to be unmixable. The second mixture steps creates rubber compounds, which are used in the next production step.

Component preparation

The rubber compounds created are manufactured into the components necessary to build a green tyre. The components are prepared by means of extrusion, calendaring or bead building.

Extrusion is the process of squeezing the rubber compound through a die to form thick sheets. The rubber is first heated to make it elastic and once extruded cooled again. This process is used to produce tread and RC strips.

During calendaring, a nylon cord is rubbered by a series of hard pressure rollers. Afterwards, it is cut in a proper angle into specific length and width. This process is used to produce breakers, the plies and the inner liner.

The bead-making process begins with rubber coating the steel by extrusion. The beads are finished when the bead filler has been extruded and applied to the bead.

Tyre building

The building of the green tyre consists out of two steps. First are two RC strips applied to the sidewalls of the inner liner at the pre-assembly machine. Now, all components are ready to be assembled at the Space Master building machine. The machine is not fully automatic, so the operator needs to perform some actions manually. The tyre is built inside out on a drum, so starting with the inner liner and its attached RC strips. Next is the ply applied to it, followed by two breaker layers and another layer of ply. Those four layers are all applied in opposing angels, to strengthen the tyre and to make sure that the tyre is not angled inflated. Afterwards, the beads are assembled to both sides, followed by the final layer of tread.

Curing
To make the green tyre worthy for the road, it has to be cured. This is done by placing the green tyre in a curing mould and applying heat and pressure such that the green tyre is inflated in the shape of the mould. The curing press of SM consists of two openings in which a curing mould can be placed, so two tyres can be cured at the same time. Figure 10 shows the curing process.

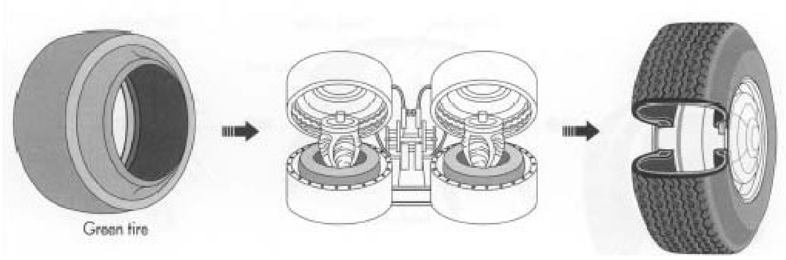

Figure 10 Curing Process, Reprinted from "The Unofficial Global Manufacturing Trainee Survival Book", (Apollo Vredestein B.V., 2015)

Mounting
The final step in the production process of SM is the mounting of a rim to the tyre. The rim mounted to the tyre is always supplied by the customer.

2.1.1 Process flow diagram

Having identified all steps of the production process, a process flow diagram has been created for SM tyres shown in Figure 11. This visualizes the relations between the production steps, thus also the general inputs and outputs of each process. Important to notice for this research is that the green tyres go to intermediate storage before going to the so-called machine storage. Machine storage is the storage in front of the machine, in this case, the curing press.

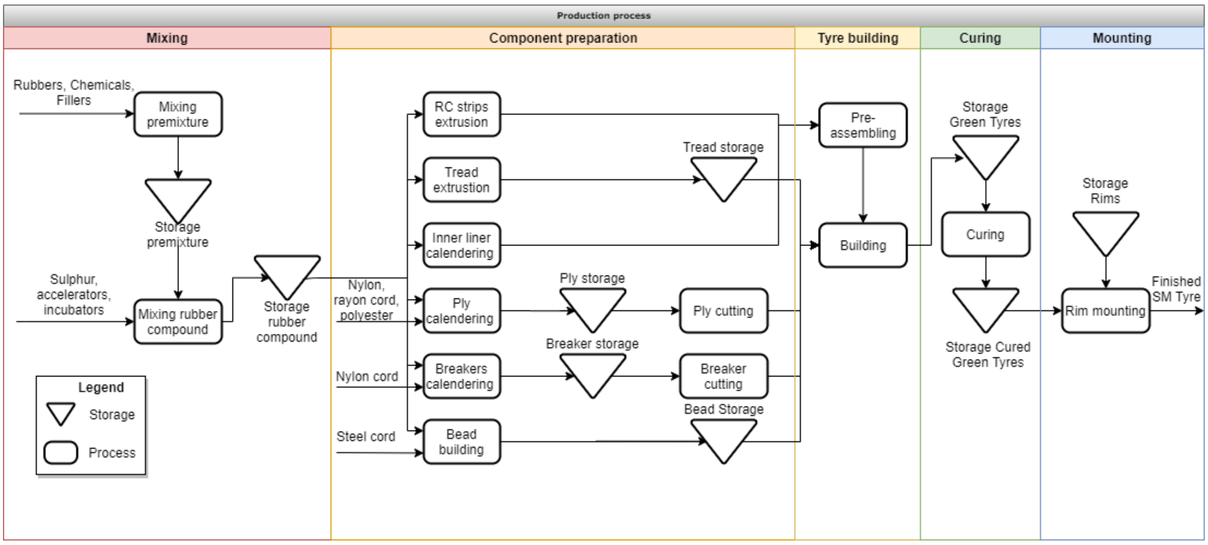

Figure 11 Process flow diagram

2.2 Production planning

A production planning is responsible for ensuring the availability of all materials, part of assembly at the right time, at the right place, and in the right quantities (Kiran, 2019). Within Apollo Vredestein, this process starts with an annual plan of order quantities received from the sales department. Per definition can be referred to this annual plan as the master production schedule (MPS), being a plan for the production of individual final items per time period (Karl, 2019). This annual plan is usually based on forecasts, but can also be based on orders or demand predictions from customers itself. Those yearly forecasts are necessary, mainly because the delivery lead time of the suppliers from the raw material is long. Therefore, the purchases of raw materials made are based on this MPS. The MPS is converted into a production planning by using the bill of material (BOM). On the BOM is the relation shown between the materials and finished products, which are calculated with material requirements planning (MRP) (Smartsheet, 2020). MRP is thus used at Apollo Vredestein as a planning and control system for inventory, production and scheduling. MRP is a push system of inventory control, as the amount and type of products to produce are mainly forecasted, and thus made-to-stock, and it pushes the products to the consumers (Smartsheet, 2020).

The production planning made directly from the annual plan is the one for curing. Curing has been identified as the bottleneck. The capacity of curing is therefore equal to the capacity of the entire plant (LeanProduction, n.d.). Idle time during the curing phase has a direct impact on the output of the plant and thus should the curing presses be utilized completely. Next, this is the phase where generally speaking a tyre becomes specific and where planning and demand converge. A green tyre SKU can sometimes become multiple SKUs of finished tyres. Although this is not the case for SM where planning and demand already converge in the building phase, it is chosen to have one type of production planning for the entire plant starting in the curing phase. Based on the curing production planning and thus the planned orders from curing, the building production planning is made. The production planning for components is similarly based on the demand of the building phase. The one exception in this process is that the mixing orders are not based on the following phase, but on the curing phase. The reason for this is that this phase is less flexible. There are namely huge differences between the mixing batches and daily demand, as well as that the rubber compound produced in the mixing phase needs ageing time before it can be processed further. Figure 12 shows the general production planning as discussed above.

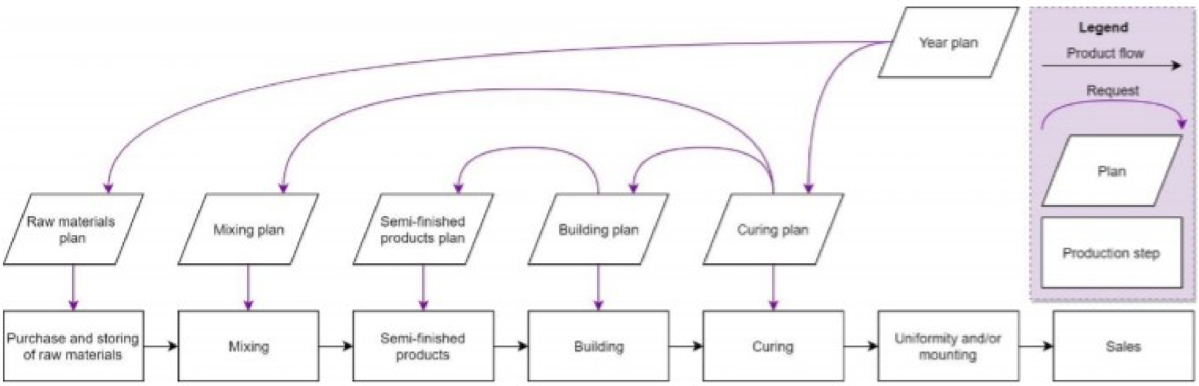

Figure 12 General production planning. Reprinted from "A bottleneck analysis to increase throughput at Apollo Vredestein B.V.", (Plomp, 2019)

2.2.1 Curing production plan

The curing production plan is the input for the building production plan and the determination of the curing production plan indicates the demand process of the building phase. The plan is made for a time span of four weeks, which is the planning period. In essence, the planning is static and thus not revised. Therefore, there is no demand uncertainty within the scope of this research.

The input of the curing production planning is the number of moulds per SKU which are deployed daily. This number is based on the constraint that there is a maximum of five SKUs which can be cured at the same time, to control the number of different component inventories. This number is also based on the curing production norm, which is that each mould produces 34 cured tyres per shift. This is a gross norm and does not include mould changing and maintenance.

The curing production planning is made within PIBS. PIBS is the production information and operating system used with Apollo Vredestein to manage a lot of processes within the plant, including the planning. It determines for all eleven curing presses which moulds are placed inside. As stated in Section 2.1, each curing press consists of two openings, A and B, in which a mould can be placed. In total is determined which 22 curing moulds are placed in which curing opening. It is also possible to leave a curing opening empty. There are no technical constraints because every mould fits in every opening of a curing opening. Also, it determines during which shift a curing mould should be changed to another curing mould or when the press should be stopped. Mould change only happens when the inventory for this mould is zero. The exact change moment cannot be determined, because the planning is based on a gross norm. The production norm can be corrected within PIBS by the expected efficiency of the curing press. The efficiency is the percentage of time the curing press is actually curing green tyres. This parameter is set to its maximum, to make sure there are sufficient green tyres demanded. The curing production planning is thus based on the maximum capacity. Therefore, the demand per opening is known, constant and continuous. The demand per SKU is thus always a multiple of 34, the demand per opening per shift.

2.2.2 Building production plan

The building production plan is the supply for the green tyre inventory and the curing presses. There is too much deviation from the building production planning as stated in Section 1.4, so there is supply uncertainty. The building production planning is made for a timespan of six shifts. A rolling horizon planning procedure is used for this planning. The planning is static during a shift, in literature referred to as the first-period decision (Nahmias & Olsen, 2015). After every shift, it is revised, based on the production of the previous shift, and reran for the next six shifts. Determined is for all eight building machines which and how many green tyres have to be built when another SKU has to be built and which.

The building production planning balances the supply, the total production planned, and the demand of curing per machine per shift. This definition is also used for MPS (MRPeasy, n.d.). It determines the planned order releases using MRP (Nahmias & Olsen, 2015). An order of green tyres consists of a batch size of one specific SKU. In Figure 13 the MPS of the building phase can be seen, converted from a building production planning used within Apollo Vredestein which can be found in Appendix A. It has been converted to put it in an industrial engineering perspective with related terms. Shown in this MPS is that the demand is consistent for the coming six shifts. Also, the production is consistent for this time span because it concerns the same SKU. The planned order releases are included in the MPS as well. In shift

	Machine 43							
			Shift 1	**Shift 2**	**Shift 3**	**Shift 4**	**Shift 5**	**Shift 6**
Initial inventory		+	**32**	**53**	**74**	**95**	**116**	**137**
Demand of curing		-	**68**	**68**	**68**	**68**	**68**	**68**
Production per order	Order 738: SM197518-G		63	0	0	0	0	0
	Order 739: SM197518-G		26	64	0	0	0	0
	Order 740: SM197518-G		0	25	65	0	0	0
	Order 741: SM197518-G		0	0	24	66	0	0
	Order 742: SM197518-G		0	0	0	25	67	0
	Order 743: SM197518-G		0	0	0	0	22	68
	Order 744: SM197518-G		0	0	0	0	0	21
Total production planned		+	**89**	**89**	**89**	**89**	**89**	**89**
Ending inventory		=	**53**	**74**	**95**	**116**	**137**	**158**

Figure 13 MPS of the building phase. Adapted from "Free Master Production Schedule" (MRPeasy, n.d.)

one, produced is for orders 738 and 739, respectively 63 and 26 green tyres. The remaining part of order 739 is produced in shift two.

2.2.2.1 SIPOC Diagram

To understand the inputs and outputs of this planning's process, a SIPOC diagram is used. SIPOC stands for Supplier, Input, Process, Output, Customer and is a tool that summarizes the inputs and outputs of one or more processes in table form (Bridges, 2018). First, the process is explained, followed by the input and their suppliers and finally the output and the customer. The diagram is shown in Figure 14 and is scoped to the building production planning process. The determination of the production planning of the components, which is coherent to this planning, is not included because it is out of scope of this research.

Supplier	Input	Process	Output	Customer
Curing production planning	- Number of moulds deployed per SKU - Number of mould changes per SKU	Building production planning in PIBS ↓		
Industrial Engineering	- Curing production norm - Mould change norm -Building production norm - Efficiency - Batch size per order - Plan horizon	Optimizing the planning based on GT inventory ↓	- Building production plan -Orders	Building phase
PIBS	- Initial inventory			
Product Industrialisation	- Bill Of Materials - Technical constraints	Optimizing the planning based on size and priority		
Planner and/or Coordinator	- Preference SKUs - Number of building machines -Number of employees			

Figure 14 SIPOC diagram

Process

The building production planning is determined within PIBS, based on the curing demand, input parameters and the regular number of building machines and employees. Next, this planning is manually optimized by the planner based on the initial inventory. This includes an adjustment if the number of building machines or employees differ from what was expected. It is done to minimize the NGT percentage. Finally, the planning is optimized based on size and priority. The reason for this is to minimize the rebuilding time from the machine to build another SKU. The rebuilding time is the setup time needed when the SKU changes. A size change takes around 30 minutes and an inch change takes around two hours. Therefore, the planner tries to minimize the inch changes while the input for the curing presses remains sufficient. A tool for this included in PIBS is assigning preference SKUs to a building machine.

Inputs and suppliers

An input of the building production plan is the demand of the curing phase. The demand consists of the number of moulds deployed per SKU and the number of mould changes per SKU. A mould change only happens after a multiple of 24 hours. This demand is similar to the input of the curing production planning but then expressed as the number of green tyres per SKU. This is done by using the production norms. The production norm is one of the parameters determined by the Industrial Engineering department, see Section 2.4.

Another input is the building production norm. This production norm differs per SKU and machine. Like the curing production norm, it is based on the optimal cycle time of the building of a green tyre. It can also be corrected by the efficiency, which is done in this case. Those two parameters are also determined by the Industrial Engineering department. The final parameters they deliver are the batch size per order and the plan horizon.

The initial inventory per SKU is tracked within PIBS as explained in Section 2.3. Finally, the BOM and the technical constraints are considered by Product Industrialization. The constraints are only process technical, such as that not every inch size can be built on every building machine.

Output and customer
The output of the SIPOC is the building production planning per machine including the generated orders, which is used in the building phase.

2.3 Green tyre inventory

As stated in Section 2.1.1, there is inventory between the building and curing phase. Meaning that the green tyres do not go directly to the machine storage, but to intermediate storage. Currently, the green tyre inventory is tracked as the sum of this intermediate storage, the machine storage of green tyres of the building machines and the machine storage of green tyres at the curing presses. The green tyre inventory is work-in-process inventory, waiting in the system to be processed (Nahmias & Olsen, 2015). The green tyres are stored on racks. On a rack 18 or 24 green tyres can be stored, depending on the SKU.

The green tyre inventory is tracked within PIBS. However, this information is based on predictions. The building coordinator asks every building operator roughly an hour before the end of the shift to register the number of green tyres he will have built at the end of the shift. This number is based on the current green tyres built, which the building machine itself tracks, and a prediction for the last part of the shift. They update PIBS with this information. PIBS corrects the green tyre inventory with the reported green tyre production, which was initially increased by the planned green tyre production. The same happens in the curing phase, where PIBS corrects the green tyre inventory with the reported green tyres cured.

Both information updates include predictions, so the actual green tyre inventory and the one in PIBS usually differ. Therefore, at the beginning of each shift, a curing operator counts the current green tyre inventory and reports this to the shift planner. The shift planner updates the green tyre inventory level with the actual green tyre inventory and adapts the building production planning on this.

2.3.1 Determination of the green tyre inventory

The demand from curing per SKU is known for four weeks ahead. Therefore, we do not have demand uncertainties within the green tyre inventory. The demand per SKU is not consistent for every shift. However, it is consistent for a multiple of shifts as shown in Figure 15. This

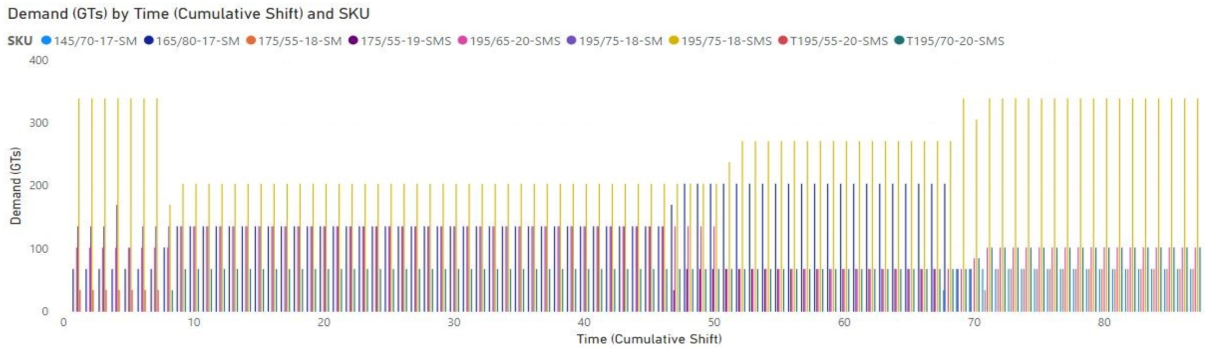

Figure 15 Curing demand per SKU per shift in February 2020

consistency is always a multiple of 24 hours because mould changes are planned per 24 hours. On the other hand, the demand per opening is consistent, namely 34 green tyres regardless of the SKU assigned.

Within PIBS, the green tyre inventory level is only tracked and no optimal level is determined. The level is determined by the shift planner, who strives to have sufficient inventory for the current eight-hour shift to account for uncertainties. However, no safety inventory or safety lead time is maintained. The eight hours are not predetermined, it is only an indication and used to steer. It is not included in calculations within PIBS. However, a transportation time of 60 minutes is maintained to bring a green tyre from its location to the green tyre inventory or curing press. This can be seen as a safety lead time, as Industrial Engineering maintains roughly 5 minutes for this transportation time. More information about Industrial Engineering can be found in Section 2.4. The order quantity is fixed per SKU because the green tyres built are based on orders as stated in Section 2.2.2. Therefore, the green tyre inventory also has cycle inventory, which is a result of production of lots larger than one (Chopra & Meindl, 2016). The whole order is not delivered at the same moment, but partially per rack. The delivery quantity is therefore fixed, with one exception. If it is the last part of the order, the rack is delivered not entirely filled.

2.3.2 Steering by the coordinators

The coordinators are in a position to steer the production, such that the green tyres are produced which are necessary. To implement KPIs monitoring and controlling the green tyre inventory, first should be elaborated how it can be monitored and controlled. Currently, this is done the following:

- **Decision of the number of curing presses deployed**
  The coordinator can decide in cooperation with the planner to stop a curing press because the inventory is insufficient.

- **Decision of the number of building machines deployed**
  The coordinator can decide in cooperation with the planner to stop a building machine because there is more than sufficient inventory.

- **Allocation of operators**
  The coordinator can decide which operator works at which machine or press. There are several levels of operators, differing in experience and capabilities. More productive operators produce more output. Those can be allocated towards the most critical SKUs. Operators in education produce less output and can be allocated to less critical SKUs. Operators who can work in both the building and curing phase bring flexibility and can be allocated to the necessary phase.

- **Substitution during breaks**
  The coordinator can decide to substitute an operator during his break, to increase production.

2.3.3 Green tyre inventory in PCT

The green tyre inventory in PCT is also tracked within PIBS but without predictions. Observing this method can help to create a more accurate green tyre inventory for SM within PIBS. PCT has a scanning system to track inventory within PIBS. When green tyres are built, building operators put them on a rack. Each green tyre rack contains one SKU and has a standard quantity depending on de size of the SKU. When the rack is full or when the building coordinator changes to building another SKU, he gives a signal within PIBS. The green tyre inventory increases by the standard quantity. A transporter receives this signal, picks up the rack and brings it to the assigned place of green tyre inventory. This can be both the intermediate storage and the machine storage. When the quantity on the green tyre rack differs from the standard quantity, the transporter can change it. The final action is the confirmation that the green tyre rack is at the assigned location. Just like the building operator gives a signal when a rack is full, the curing operator also reports in PIBS when he needs a green tyre rack as input. A forklift trucker receives the order with an assigned rack, which is based on the first in, first out principle. Next, he scans the green tyre rack, brings it to the curing press and finally presses agree to confirm that the green tyre rack is now in the machine storage. PIBS knows thus the actual level and location of the green tyre inventory. This scanning is also done within the SM line, but the information is not used to track inventory.

2.3.3.1 TOC implementation in PCT

Within Apollo Vredestein, TOC has already been implemented in the PCT production line, including KPI implementation. The KPIs selected for PCT can help to identify KPIs for SM. The most important finding was that the wrong questions were asked starting from the top levels. Those questions were based on the KPIs, which are related to the number of tyres produced instead of the necessary numbers of tyres produced. Therefore, they introduced two new KPIs shown in Figure 16, the quality of inventory and NGT.

- **Qualitative inventory**: *Number of moulds < 8 hours inventory*
  This KPI shows that which moulds are critical. It indicates on what SKUs to focus, in the current shift.

- **NGT**: *(Idle time because there are no green tyres / (Total available time – planned downtime for maintenance)*
  This KPI shows what the idle time of curing was because there was no input, which are the green tyres. It indicates how the performance has been in the past.

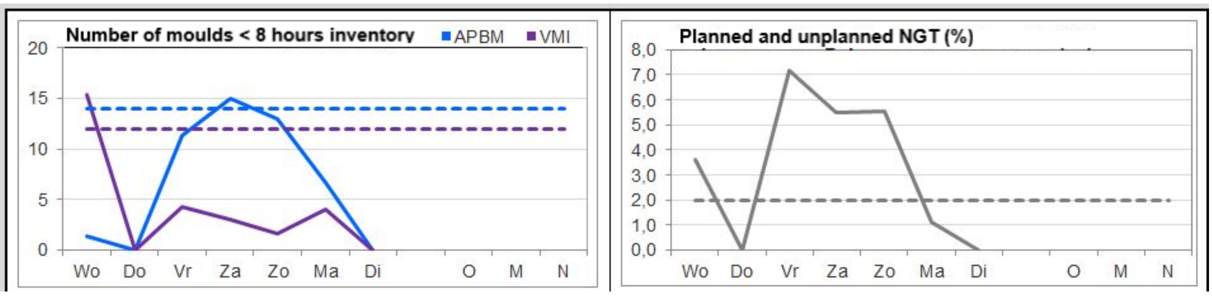

Figure 16 New KPIs in the daily report of PCT

2.4 Stakeholders

To identify the stakeholders, their position and objectives, the managerial level application of the TOC should be taken into account. From the top should the TOC education be brought to the lowest level of the organization, to the lowest level kings (Goldratt, 1990). These are the people who are responsible for the building phase, which are the coordinators. The top, to which the coordinators need to report, need to work according to TOC and are therefore involved as well. Based on this knowledge, a stakeholder matrix has been created as seen in Figure 17.

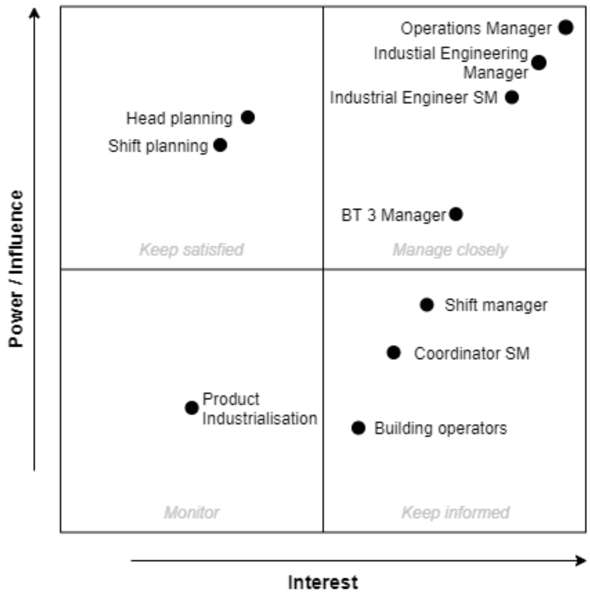

Figure 17 Stakeholder matrix

Operations Manager
Being the top, he is responsible for the ins and outs of the plant and steers the business team managers and shift managers based on costs, quality and quantity.

KPI Objectives:
- The implementation should not be costly.
- It should encourage an increase in quantity without a decrease in quality.
- It should be in line with TOC.

Industrial Engineering Manager
He is responsible for the Industrial Engineering department and thus the increase in efficiency and optimization of all production processes of the plant. Also, he is responsible for this assignment and the supervisor of this research from Apollo Vredestein.

KPI Objectives:
- It should give insight into qualitative inventory. In other words, the current inventory compared to the inventory which the curing phase needs to ensure throughput at a certain period of time for a certain time span.
- The coordinators should be involved.
- It should be in line with TOC.
- It should be effective.

Industrial Engineer SM
He is responsible for the increase in efficiency and optimization of the SM production. He has more detailed knowledge about and access to specific data and information of the SM production process. He is also concerned with calculations about demand, capacity and budget.

KPI Objectives:
- It should stimulate an increase in throughput of the plant.
- It should stimulate the building phase to be more reliable suppliers.
- It should represent an accurate inventory level.

Business Team 3 Manager
He is responsible for keeping the process of SM running, including the machinery, maintenance and process optimization. He has to report the performance to the operations manager and steers the coordinators. His objectives are that the daily production goal is reached, the production and working environment is safe, that the produced products are of high quality and to have a cost-effective way of working.

KPI Objectives:
- It should stimulate the output of curing without a decrease in quality.
- It should stimulate a cost-effective way of working in both the building and curing phase.

Shift Manager
The shift manager is during his shift responsible for the flow performance of the plant, as well as reaction on daily problems and everything related to the manning of his shift, like motivation and the sick leave. His main objectives are on time in full delivery on daily basis and low absenteeism. Other objectives are that the tyres meet the quality standards and to have a maximum output relative to hours worked.

KPI Objectives:
- It should encourage the production of the demanded output of the building and curing phase, without a decrease in quality.
- It should encourage motivation for the coordinators and operators.

Coordinators
The coordinators are responsible for coordinating and managing the SM production process. They steer the building and curing operators and they are responsible for the output of the building and curing phase. As they will be the main user, the KPIs should help them steer. During meetings, missing insights in their eyes were discussed to realize the monitoring and controlling. Those are added to the KPI objectives beneath.

KPI Objectives:
- It should give insight into the actual inventory levels at the start of the shift.
- It should give insight into the number employees in the building and curing phase planned in future shifts, based on manning and machine capacity.
- It should give insight into the demand for future shifts.
- It should stimulate an increase in output.
- It should not be time-consuming to work with.

Building Operators
The operators, in this case the building operators, are responsible for building the tyres and updating the number of tyres built. Also, they are responsible for checking the qualifications of the components before they use it. They are only steered based on the KPIs, so objectives are not relevant. To keep them motivated, steering should be done with realistic expectations.

Product Industrialisation (PI)
PI is responsible for designing and optimizing processes by increasing capability and stability. For the latter is the process engineer SM is responsible. He is responsible for the quality of the tyres and has a lot of knowledge about the production process.

KPI Objectives:
- Green tyres are not allowed to be too longer than 48 hours in inventory to prevent shrinkage due to temperature, so it should include a maximum level.

- The inventory levels should include a distinction between summer and winter.

Head Planning
He makes the curing planning from a list of demanded SKUs, taking into account the constraints mentioned in Section 2.2.1. He is mainly involved to gain knowledge about the planning process and the effects the curing planning has on the plant. Objectives are therefore not relevant.

Shift planner
Every shift there is a shift planner, who derives the operational planning from the curing planning and controls it during this shift. He has direct contact with the shift manager and coordinators, and updates if necessary the planning based on the previous shift by making last-minute adjustments. He can, for example, decide to plan an intentional stop of a curing press, to bring the green tyre inventory to the right level again.

KPI Objectives:
- It should stimulate to keep up with the planning to minimize last-minute adjustments.
- It should stimulate the production of the necessary green tyres.
- It should stimulate an increase in the accuracy of the inventory levels.

2.4.1 Discussion
The criteria for KPI selection are based on the stakeholders criteria. In general, the stakeholders have a lot of emphasizes on throughput without a decrease in quality or increase in costs. Important is that this should be defined as the throughput of the entire system or product availability for the demand of the next production step. The KPI implementation is a means to increase product availability and thus throughput, so this objective is not a criteria for KPI selection. The same counts for the reliability, motivation and stimulation of the building phase. Accuracy of the inventory levels and inventory control in line with TOC is part of the input, so these are also no criteria for the KPI selection. Currently, there is no proof for a maximum time green tyres can be stored and still be cured effectively in summer nor winter. The maximum level of 48 hours is never reached because there is no production capacity for that. Therefore, both criteria of the PI Engineer SM will be excluded. Next, the missing insights of the coordinators can be seen as supporting analytics, which are explained in Section 3.2.4, leaving us with the following criteria for KPI selection:

- It should give insight into qualitative inventory.
- It should be effective.

Effective is a goal-setting of a KPI, such that the KPIs effectively represent its goal “insight in qualitative inventory”. Therefore, the criteria for KPI selection will be that the KPI(s) give insight into qualitative inventory, based on effectiveness criteria.

3. Literature review

In this chapter, a literature review is conducted regarding inventory control and KPI implementation. To determine KPIs to monitor and control green tyre inventory first should be determined how this inventory can be controlled. Therefore, in Section 3.1 inventory control and its objectives are discussed answering research question 5. Next, in Section 3.2 we discuss KPIs to answer research questions 6 till 10. We list existing KPIs to monitor and control inventory in Section 3.2 and discuss KPI effectiveness in Section 3.2.1. Afterwards, we research how many KPIs should be selected in Section 3.2.2. Next, we discuss KPI selection methods in Section 3.2.3 and KPI visualization in Section 3.2.3. The conclusion of the chapter can be found in Section 3.3.

3.1 Inventory control

Inventory exists because of a mismatch between supply and demand of two steps in a process. This mismatch can be intentional, to reduce order costs or to increase the level of product availability. On the other hand, having inventory increases the inventory holding costs (Chopra & Meindl, 2016). Inventory should only be accumulated when the advantages outweigh the disadvantages (Slack, Brandon-Jones, & Johnston, 2016). To determine the inventory level, a trade-off between holding costs, order costs and product availability should be made. The aim is to reduce inventory in ways that do not increase costs or reduce responsiveness (Chopra & Meindl, 2016).

Cycle and safety inventory

The inventory level consists of cycle inventory and safety inventory (Chopra & Meindl, 2016). Cycle inventory, also known as working inventory, is the average amount of inventory used to satisfy demand during a given period. This inventory is expected to be sold and produced to reduce order costs. Cycles occur in the inventory level, because companies produce in large lots to exploit economies of scale in the production, transportation or purchasing process (Chopra & Meindl, 2016).

Safety inventory, on the other hand, is inventory held to encounter uncertainties in supply and demand together with lead times (Axsäter, 2015). Next to uncertainty, it is also held to increase product availability (Chopra & Meindl, 2016). It acts as a buffer in case of a stockout, which results if an order arrives when the product is not available. The safety inventory levels depend on the service level desired by the organisation (Chopra & Meindl, 2016). In Figure 18, inventory levels are depicted, representing the relation of inventory with cycle and safety inventory. Here, the safety inventory can be interpreted as the minimum level of inventory.

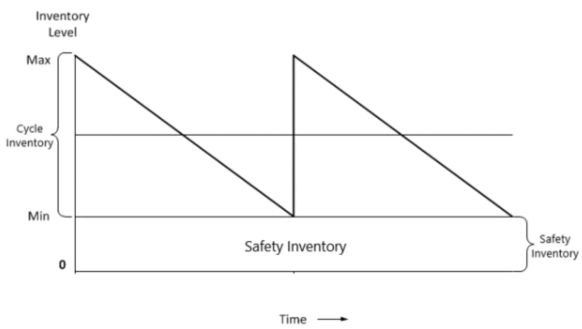

Figure 18 Inventory levels, Adapted from Safety Stock- How To (2016)

Safety lead time

To buffer against uncertainties and product availability, a safety lead time can also be used. This means that the product is available a specified time before it is necessary. The main difference is that safety inventory demands every item in inventory and a safety lead time demands the items necessary in a specified period. Generally speaking, safety lead times make sense if the essential uncertainty is in the production lead times. Safety inventory makes sense if the essential uncertainty is in the demand forecast. Often, a mixture of both is used in practice (Nahmias & Olsen, 2015).

3.1.1 Inventory classification

In principle, each SKU in inventory can be controlled individually (Axsäter, 2015) and can have a different profitability (Nahmias & Olsen, 2015). However, determining control techniques for every SKU is not convenient in a multiproduct system. Therefore, it is easier to classify the inventory SKUs and determine this per class. The ABC analysis is a well-known technique for inventory classification. The ABC analysis is based on the concept that a relatively small percentage of the SKUs account for a large share of the total sales volume (Axsäter, 2015). The three SKU groups are labelled A, B, and C respectively. Group A is seen as the most important and should be controlled the most precisely, whereas a minimum degree of control should be applied to group C (Nahmias & Olsen, 2015).

3.1.1.1 Discussion

However, inventory classification based on annual sales is not in line with TOC, as it does not influence the equipment or production (Ye, 2004). He suggests to identify A items as items installed to the bottleneck, items where the need cannot be predicted or items having a few suppliers with a long purchase lead time. B items include items where the need can be predicted. Next, C items are classified as items with many suppliers and/or short purchase lead time. Even D items are introduced, which are general items installed at some even all equipment (Ye, 2004). All these divisions are not relevant regarding the green tyre inventory. All can be checked in advance when they are necessary, they are all supplied by the building phase, and for all is a comparable lead time enhanced. One hour of idle time of the bottleneck is equal to one hour of idle time of the entire system, no matter which SKU is concerned. All SKUs are equally important. Therefore, classification of SKUs will not be included.

3.1.2 Inventory control policies

To control inventory and to determine inventory levels, parameters and target levels, an inventory control policy should be chosen to work with. Inventory control is used to balance conflicting goals (Axsäter, 2015) and thus to balance the trade-off stated in Section 3.1. According to Chopra & Meindl (2016), inventory control policies consists out of the following decisions:

- When to reorder?
- How much to reorder?

Those decisions are based on the inventory position, the anticipated demand and the lead time (Axsäter, 2015). The inventory position does not only include physical inventory on hand, but also outstanding orders which are not yet arrived, minus the backorders. Backorders are units that have been demanded but not yet delivered. The anticipated demand is the number of products the customers are likely to purchase and the lead time is the time from the ordering decision until the ordered amount is available on the shelf (Axsäter, 2015).

When to reorder is based on the reviewing policy. It is divided into two types, periodic review and continuous review. Periodic review means that the inventory level is known at discrete points in time only, while with continuous review the inventory level is known at all times (Nahmias & Olsen, 2015). Continuous review is more accurate, but it is less predictable. Next, it is harder to administer and more costly due to the workload and necessary computer control

(Sherman, 2019). Knowing when to reorder, the second question is which reorder policy will be used. This can be a fixed quantity or a variable quantity. Discussed will be the combinations of these choices, as discussed by Arends (2016). These are summarized in Table 1. In addition, the (R, s, Q) policy is discussed. In Table 2, the definitions of the variables used are found.

	Fixed order quantity	**Variable order quantity**
Periodically review	(R, Q), (R, s, Q)	(R, S)
Continuous review	(s, Q)	(s, S)

Table 1 Inventory control policies

Variable	**Definition**
R	Review period
Q	Order quantity
S	Order up to level
s	Reorder level

Table 2 Variable definitions

(R, Q) Policy
The (R,Q) policy is a periodically review policy. Every R periods, a fixed quantity Q is ordered. When the inventory is sufficiently low, even a multiple of Q can be ordered. Therefore, this policy is also known as a (R, nQ) policy (Nahmias & Olsen, 2015). This quantity is equal to the average demand during period R, assuming regular demand during each period. This model is the simplest to implement, but the least accurate.

(R, S) Policy
The (R,S) policy reviews periodically every R periods, like the (R,Q) policy. However, instead of ordering a fixed quantity, ordered is up to level S (Winston, 2004). This is done by reviewing the on-hand inventory level and ordering the difference between that level and the order-up-to level S. If the on-hand inventory is greater than S, there is no need to order. Contrary to the (R, Q) policy, this model can work with variable demand. Other advantages are that replenishments can be coordinated and order times can be predicted with certainty. A disadvantage is that it has higher holding costs compared to continuous review policies (Winston, 2004).

(s, Q) Policy
The (s, Q) policy is a continuous review policy. Whenever the inventory reaches a reorder level s, a fixed quantity is ordered. This fixed quantity is usually a predetermined batch size, minimizing the total cost. A disadvantage of this policy is that order times are uncertain and that the system is not optimal for larger orders (Winston, 2004). However, this policy reacts more quickly to inventory fluctuations than the (R, S) policy and reduces, therefore, the chance of stockouts (Willemain, 2019).

(s, S) Policy
The (s, S) policy is a continuous review policy like the (s, Q) policy and orders when the inventory level is less than or equal to s (Winston, 2004). The order quantity is determined as with the (R,S) policy. The on-hand inventory level is reviewed and the gap between the inventory and S is ordered. This policy is most responsive and has the lowest holding costs because the order size is adjusted to the order up to level (Willemain, 2019). The main disadvantage is that determination of both variables is extremely difficult (Nahmias & Olsen, 2015).

(R, s, Q) Policy
The (R, s, Q) policy is a combination of the (R, Q) and the (s, Q) policy. It is a periodic review policy. Every R periods, the inventory position is reviewed and when it is below reorder level s, an amount of Q will be ordered such that the inventory position is raised to a value between s and s + Q (Janssen, Heuts, Kok, & T., 1996). It has the advantage that it is more responsive than a (R, Q) policy as it orders based on the reorder level and that no continuous review is necessary compared to the (s, Q) policy.

3.1.3 Perishable inventory

A special inventory system is an inventory system with perishable items. Perishable items have a fixed lifetime known in advance. Most models for perishables assume that the inventory is issued based on a first-in, first-out basis (Nahmias & Olsen, 2015). The inventory system often has to be adjusted to account for perishability.

3.1.3.1 Discussion

Apollo Vredestein also uses a first-in, first-out basis for the green tyres. Next, the green tyres have a limited lifetime. They can be stored a maximum of 48 hours as stated in Section 2.4. Therefore, we can use the inventory model as long as the order quantity does not exceed the 48-hour demand. If the order quantity exceeds the 48-hour demand, then the optimal order quantity is equal to the 48-hour demand.

3.1.4 Parameters of (R, s, Q) model

Based on the policy, the relevant parameters can be determined. Generally speaking, Apollo Vredestein uses MRP as an inventory control system with a fixed order quantity and periodic review. Axsäter (2015) describes an MRP as a re-order point system. Therefore, we choose from Table 1 the inventory control policy with periodic review, a reorder level and fixed order quantity. Thus, an (R, s, Q) inventory control system will be used to control the green tyre inventory. In this section, we elaborate on how relevant parameters can be determined in an (R, s, Q) system with supply uncertainty.

To determine the order quantity, the economic order quantity (EOQ) is the most well-known formula for determining the order quantity. However, it is based on the assumption that the whole batch quantity is delivered at the same time (Axsäter, 2015). As stated in Section 2.3.1, the green tyres are delivered partially and not at the same time. Therefore, the EOQ should be extended to a finite production rate to modify for partial deliveries (Axsäter, 2015). This is known as the economic production quantity (EPQ) and can be determined with the following formula according to (Nahmias & Olsen, 2015):

$$Economic\ production\ quantity\ (EPQ) = \sqrt{\frac{2AD}{h*v*(1-P)}} \tag{3}$$

With $A = the\ ordering\ or\ setup\ costs$
$D =\ the\ demand\ per\ time\ unit$
$h =\ the\ holding\ costs\ per\ time\ unit$
$v =\ the\ value\ per\ item$
$P = the\ production\ ratio\ \dfrac{Demand\ per\ time\ unit\ (D)}{production\ rate\ per\ time\ unit\ (p)}\ such\ that\ p > D.$

The maximum height of cycle inventory when having finite production can be determined with the following formula according to (Nahmias & Olsen, 2015):

$$Maximum\ cycle\ inventory\ (CS) = Q * (1 - P) \qquad (4)$$

With $Q\ =\ the\ order\ quantity$
$P\ =\ production\ ratio\ \dfrac{Demand\ per\ time\ unit\ (D)}{production\ rate\ per\ time\ unit(p)}\ such\ that\ p > D.$

When the review period and order quantity have been determined, we can determine the reorder level with Formula 5 based on Axsäter (2015) and Nahmias & Olsen (2015). Coherent to this formula are the decisions if safety inventory (SS) and safety lead time (SLT) will be introduced. In Section 4.2, we decide to introduce safety lead time and no safety inventory. Therefore, we do not define safety inventory. Next, we adjust the formula of Axsäter (2015) by replacing the demand during lead time with demand during safety lead time, based on the description of safety lead time in an MRP system by Nahmias & Olsen (2015). We can determine the safety lead time (SLT) with Formula 6 according to Nahmias & Olsen (2015).

$$Reorder\ Point\ (s) = D_{R+SLT} + SS \qquad (5)$$

With $D_{R+SLT} = Demand\ during\ review\ period\ R\ and\ safety\ lead\ time\ SLT$
$SS = Safety\ inventory$

$$Safety\ lead\ time\ (SLT) = z * (T_{pb} + T_t) \qquad (6)$$

With $z = Safety\ factor$
$T_{pb}\ = Production\ time\ of\ a\ batch\ at\ one\ level$
$T_t = Transport\ time$

The safety lead time is dependent on the safety factor. The safety factor z can be determined based on the fill rate (fr) and cycle service level (CSL) (Chopra & Meindl, 2016). Chosen is to define the safety factor with the CSL. CSL is the percentage of review cycles that end with all demand being met. CSL is measured over time and fill rate over specified amounts of demand (Chopra & Meindl, 2016). Apollo Vredestein measures performance over time and wants to measure the green tyre availability over time, so CSL is the most relevant. We can determine z with Formula 7 and the CSL with Formula 8 according to Chopra & Meindl (2016).

$$Safety\ factor\ (z) = F_s^{-1}(CSL) \qquad (7)$$

With $F_s^{-1} = Inverse\ of\ the\ normal\ distribution$
$CSL = Cycle\ Service\ Level$

$$Cycle\ Service\ Level\ (CSL): P(D_{R+L} \leq\ \mu_{R+L} + SS) \qquad (8)$$

With $P = Probability\ of\ no\ stock\ out$
$D_{R+L} = Demand\ during\ R + L\ periods$
$\mu_{R+L} = Mean\ demand\ during\ R + L\ periods$

With the current production rate, we are not subject to a storage space capacity constraint. However, to validate this we check that the space-constraint identified by Nahmias & Olsen (2015) is inactive. This constraint only takes into account cycle inventory and is not extended to a finite production rate. Therefore, we adjust the space-constraint such that it is extended to a finite production rate with Formula 4. Next, we adjust the constraint such that the necessary space for the safety lead time is included. This results in Formula 9.

$$\sum_{i=1}^{n} w_i Q_i (1 - P_i) + w_i SLT_i \leq W \quad (9)$$

With $w_i = Space\ consumed\ by\ one\ unit\ of\ product\ i\ for\ i = 1, 2, \ldots, n$
$W = Total\ space\ available$
$Q_i = Quantity\ of\ an\ unit\ to\ be\ stored\ of\ product\ i\ for\ i = 1, 2, \ldots, n$
$P_i = production\ ratio\ \frac{D}{p}\ such\ that\ p > D\ for\ product\ i\ for\ i = 1, 2, \ldots, n$
$SLT_i = Safety\ lead\ time\ in\ products\ for\ product\ i\ for\ i = 1, 2, \ldots, n$

3.2 KPI implementation

Key performance indicators (KPIs) will be used to monitor and control the green tyre inventory, based on the parameters of the inventory control policy. KPIs measure a company's success versus a set of targets (Twin, 2019). The purpose of using KPIs across inventory control systems is to drive the most effective behaviors, decisions and strategies possible and so improve on-time deliveries (Columbus, 2018). There are plenty of KPIs that are used to measure performance regarding inventory monitoring and control on an operational level. Relevant KPIs found in literature which can be used in the building phase to monitor and control the green tyre inventory are discussed beneath. The formulas are adjusted to the building phase.

- **Delivery in full, on-time rate:** *(GTs delivered in full on time / Total GTs cured)*
  It can be used to measure the in full and on-time delivery reliability (Marr, 2012; Chopra & Meindl, 2016).

- **Inventory shrinkage rate:** *(Planned inventory – Actual inventory) / (Planned inventory)*
  It is a measure of inventory control, measuring the percentage of inventory that is lost between the two production stages (Marr, 2012; Kenton, 2020).

- **Products with less than a specified time of inventory**
  It can identify products that are in over- or undersupply (Chopra & Meindl, 2016; Apollo Vredestein, 2020).

- **Fraction of time out of stock:** *(Time per SKU with zero inventory) / (Total time)*
  It measures the fraction of time an SKU had zero inventory and can be used to identify lost sales (Chopra & Meindl, 2016; Axsäter, 2015; Nahmias & Olsen, 2015; Imane, Foaud & Abdennebi, 2016).

- **Product availability:** It measures the ability to fulfil demand out of inventory, which can be measured as product fill rate, order fill rate and cycle service level (Chopra & Meindl, 2016). As an order consists of one product, the order fill rate is not relevant.

  - **Product fill rate:** *(GTs in inventory used to satisfy demand) / (Total demand)*
    The fraction of products that were met on time from inventory measured over specified amounts of demand than time (Chopra & Meindl, 2016; Axsäter, 2015; Nahmias & Olsen, 2015).

  - **Cycle service level:** *(Cycles where all demand is met) / (Total cycles)*
    The fraction of a cycle ending with all demand being met (Chopra & Meindl, 2016; Axsäter, 2015; Nahmias & Olsen, 2015; Imane, Foaud & Abdennebi, 2016).

- **Stock cover per time unit:** *(Net stock) / (Average unit demand per time unit)*
  The time period the stock covers the demand (Phocas Software, 2019; Imane, Foaud & Abdennebi, 2016).

- **Minimum/Maximum stock levels**
  It indicates whether product stock levels are within the range or if stock levels need to be adjusted (Phocas Software, 2019).

3.2.1 Effectiveness

As stated in Section 2.4 the selected KPIs must be effective. Effective is a KPI goal setting, such that the KPIs effectively represent its goal "insight in qualitative inventory". All too often SMART is used as a means to identify effective KPIs. However, misinterpretation leaves the company often unsatisfied. Next, the probably most important attribute of a KPI is not included, which is "Actionable" (Kerzner, 2013). Therefore, the criteria for effective KPIs identified by Nahmias & Olsen (2015) are used:

- **Importance**: It measures important factors and what is measured really matters.
- **Ease**: It is relatively easy to compute and the measurement flows from the activity being monitored.
- **Actionable**: Those being measured by it can also affect its change. Kerzner (2013) adds that the user must know what action is necessary to correct the unfavourable trend and thus be able to control the outcome.

Also, input plays a role to make KPI(s) actionable. To let demand be satisfied effectively, there is little room for incorrect information (Wild, 2018). Therefore, steering on these KPIs is only effective when the information used within the KPIs is accurate. Finally, a realistic view of KPI performance is essential. It should reflect an expectation of performance, not achievement under ideal conditions (Wild, 2018).

3.2.2 Number of KPIs

When selecting KPIs, an optimum number of KPIs should be chosen. However, an optimum number of KPIs to implement is unanimous in literature (Graham, et al., 2015). Regarding the entire production process, Parmenter (2015) suggests ten KPIs. Hope and Fraser (2003) even suggest fewer than ten KPIs. Per goal, Barr (2011) states to have no more than three KPIs. Stressed is that a goal sometimes only needs one KPI, which will keep it simple. The variation of one to three KPIs per goal is confirmed by DeRuchie (2017), referring to this as a manageable number of KPIs.

Although the optimum number of KPIs is not yet existing, all leading writers agree on "less is better". More KPIs create too much confusion rather than clarification (Parmenter, 2015). Van Dijk, De Leeuw and Durlinger (2007) expand this statement by saying that it is better to have a few, for everyone clear, indicators dan a lot of indicators with several interpretations. Therefore, when choosing KPIs to be implemented, the number of KPIs should be minimized enhancing a maximum of ten for the entire process and a maximum of three per goal.

3.2.3 KPI selection

To select KPIs, a selection method must be chosen. The choice of KPIs is one of the most critical challenges an organization faces because performance measurement plays a key role in evaluating the achievement of organizational objectives (Ittner & Larcker, 1998). Selection is based on criteria identified. When the criteria are all equally important, the ones who suffice all or the most criteria are selected. In the example of Kerzner (2013), as shown in Figure 19, only the metric *Number of unstaffed hours* satisfies all criteria and is selected as KPI.

METRIC	PREDICTIVE	QUANTIFIABLE	ACTIONABLE	RELEVANT	AUTOMATED
Number of unstaffed hours	Yes	Yes	Yes	Yes	Yes
Number or % of milestones missed		Yes		Yes	Yes
Management support hrs as % of total labor	Yes	Yes			Yes
% of work packages on budget		Yes		Yes	Yes
# of scope changes		Yes		Yes	Yes

Figure 19 KPI selection based on equal importance. Adapted from Project Management Metrics, KPIs and Dashboards (Kerzner, 2013)

However, criteria are typically not of equal weight during KPI selection (Brundage, Feng, & Morris, 2017). A multi-criteria decision analysis (MCDA) is a solution for this problem. Discussed will be the most common methods identified by Velasquez and Hester (2013)

- **Multi-Attribute Utility Theory (MAUT)**

MAUT assigns utility to every consequence and then calculates the best option based on utility. It can take into account uncertainty, comprehensiveness and can account for and incorporate preferences of each consequence of each step. This level of accuracy makes this method very data-intense. It is very useful for problems having a significant amount of uncertainty and enough data available.

- **Analytic Hierarchy Process (AHP)**

The AHP is a theory of measurement through pairwise comparisons and relies on the judgement of experts to derive priority scales. It is easy to use, scalable and not as data-intense as MAUT. Its application area is problems that compare performance among alternatives. A disadvantage is the susceptibility to rank reversal, thus it should be avoided if alternatives are commonly added.

- **Fuzzy Theory**

The fuzzy theory is an extension to the set theory, which allows solving a lot of problems related to dealing the imprecise and uncertain data. Its disadvantage is that it is difficult to develop. The theory is most suitable to a problem that embraces vagueness and have no precise input.

- **Case-Based Reasoning (CBR)**

CBR uses cases similar to the problem from an existing database and proposes a solution based on the most similar cases. The main advantages are that it requires little effort and maintenance and that it can improve over time. However, it is very sensitive to data inconsistencies and that it requires many cases.

- **Data Envelopment Analysis (DEA)**

DEA measures the relative efficiencies of alternatives and rates those against each other. It is capable of handling multiple inputs and outputs. However, it cannot deal with imprecise data and assumes that all inputs and outputs are exactly known. It is suitable in areas where very precise data is available.

3.2.3.1 Discussion

The criteria identified in Section 3.2.1 to effectively represent qualitative inventory are not known to be equally important, so an MCDA has to be used. As the goal is to compare KPIs related to their performance on representing qualitative inventory, AHP is the most suitable method. It also involves the judgement of experts, which are the coordinators. This involvement is an objective of a stakeholder for the KPI implementation. Besides, MAUT and DEA require

too many and precise data, the fuzzy theory embraces a too high level of vagueness and there is only one case present for CBR, namely the KPI implementation within PCT.
As the KPI(s) should be chosen based on the goal to be effective, the proposed method of Shahin & Mahbod (2007) combining AHP with SMART goal setting is the most suitable one. However, SMART should be replaced with the goals as stated in Section 3.2, being *Importance, Ease* and *Actionable.* Therefore, the following five steps based on Shahin & Mahbod (2007) will be executed for KPI selection:

Step 1: Define and list all of the KPIs;
Step 2: Build an AHP hierarchy in which, the goal is to prioritize KPI alternatives with respect to the criteria Importance, Ease and Actionable;
Step 3: Undertake a pairwise comparison between alternatives, i.e. KPIs;
Step 4: Calculate composite priority: calculate local weights and global weights; and
Step 5: Selection of KPIs that are more relevant to organizational goals.

3.2.4 KPI visualization

The selected KPIs should be visualized. According to Kerzner (2013), it is important to choose a visualization of KPIs that best meets the end-users' need in relation to the information they are monitoring or analysing. He describes the five common KPI visualizations and the sequential steps, which are discussed beneath.

- **Alert icons**
  An alert icon is a geometric shape that is either colour-coded or shaded various patterns based on its state. It is best used when placed in the context of other supporting information or when a dense cluster of clearly labelled indicators are needed.

- **Traffic light icons**
  The traffic light icon is an extension of the alert icon and has the advantage that it has a widely recognized symbol of communicating a good, warning and bad state. It is best if it is used by a wide audience.

- **Trend icons**
  A trend icon represents how a KPI is behaving over a period of time, which can be moving toward a target, away from a target or static. It is used in the same situation as alert icons, or as a supplement to a KPI providing movement over time.

- **Progress bars**
  A progress bar represents relative progress towards a positive quantity of a real number. Negative numbers do not work well. Indication of specific targets and limits can be done by adding colour and alert levels. It is convenient to use when you want to compare multiple KPIs with the same measure along the axis.

- **Gauges**
  A gauge assesses both positive and negative values along a relative scale. It should be used for dynamic data that change over time in relation to underlying variables. Alert levels can be included and it is convenient for more sophisticated data visualization packages.

Supporting analytics
It is possible to add supporting analytics to the KPIs, which a user can view to help diagnose the condition of a given KPI. Those are often visualized in the form of traditional charts and tables or lists (Kerzner, 2013).

Labels

When a KPI visualization has been chosen, it is important to label it. Labels are used to give context for the data they are looking at, for both scale and content. The distinctiveness of these depend on how often the KPI is reviewed. With frequent reviewing, the labels can be more conservative by using smaller fonts and less colour contrasts (Kerzner, 2013). Labelling has some common pitfalls, for which prevention suggestions are identified by Stephen Few. It is important to supply adequate context for the data as to what is good and bad performance. Second, a graph should have no more than a five-point scale and avoid unnecessary precision. Lastly, it is better to start the scale of the graph from zero instead of midway (Parmenter, 2015).

Size, contrast and position

The final step is to determine size, contrast and position. Those elements determine what will grab the user's eye first. The size is mainly important when there are several KPIs. The most important KPI should be proportionally larger. Next, the colour or shade contrast help determine how the user focuses his attention (Kerzner, 2013). It should be used to draw attention to key pieces of data (Marr, 2019). The use of colour also has a common pitfall identified by Stephen Few, being the use of a lot of colours. Many readers cannot distinguish between certain colours, and therefore it is better to be a minimalist with colour (Parmenter, 2015). The position also plays a role where the user focuses his attention and is mainly important when there are multiple KPIs. The top-right side of a rectangular will be the user's first focal point, all other factors held constant, and should be used to place the most important KPI (Kerzner, 2013).

3.3 Conclusion

In this chapter, theoretical knowledge regarding inventory control and key performance indicators is discussed.

In Section 3.1, first, the concept inventory is explained. We will use inventory control mainly to increase product availability. Next, inventory control is necessary to determine the target levels of the KPIs. For a minimum inventory level a safety inventory, safety lead time or both should be determined. To control inventory the items can be classified and a control policy should be chosen. Classification is not relevant and not in line with TOC. Five inventory control policies are discussed and chosen is to work with an (R, s, Q) inventory control policy for the green tyre inventory. We can work with this policy if we include the constraint that the order quantity may not exceed the 48-hour demand. Finally, relevant parameters of an (R, s, Q) policy with supply uncertainty are discussed.

In Section 3.2, KPIs are discussed. Existing KPIs to monitor and control inventory are listed. Next, we decide that a KPI is effective when it is important, easy and actionable. To make steering on KPIs effective, the input should be accurate and realistic. The one existing rule for an effective number of KPIs is 'less is better'. To give an indication, this number for a goal should range between one and three. To select KPI(s), first we discussed how to select KPIs when all criteria are equally important. Next, MCDA methods are discussed which can be used if the criteria are not equally important. Chosen is to select KPIs based on AHP with the goal setting to be effective. Lastly, discussed is how a KPI can be visualized effectively. Also, effective use of labelling, size, contrast and position is discussed.

4. Solution design

This chapter focuses on the solution design to increase product availability of the green tyres. In Section 4.1, we first present a flowchart of the solution design. Second, we define in Section 4.2 the purpose and the parameters of the (R, s, Q) inventory control policy. We execute this by answering the questions as stated by Chopra & Meindl (2015) in Section 3.1.2. Next, in Section 4.3 we select the KPI(s) with AHP with respect to importance, ease and actionable. We follow the steps as stated in Section 3.3.1. Finally, in Section 4.4 we define how to visualize the selected KPI(s) chosen in Section 4.3. Section 4.5 concludes the chapter.

4.1 Flowchart solution design

The flowchart of the solution design in Figure 20 shows all steps which will be executed to increase the product availability of green tyres. First, in Section 4.2 we set up the (R, s, Q) inventory control policy chosen in Section 3.1.4 to buffer against supply uncertainties. Next, in Section 4.3 we select KPI(s) to monitor and control the green tyre inventory. The goal of the KPI(s) is that the coordinators can effectively steer on the quality of the green tyre inventory and the green tyre availability. Based on the selected KPI(s), we define how we are going to visualize the KPI(s) in Section 4.4. Then, we are going to implement the solution design in Chapter 5. In Section 5.1 we implement the inventory control policy to buffer against supply uncertainties. Next, we validate this implementation with historical data. This is done by checking if the policy indeed increases the product availability to a minimum of 98%. Afterwards, in Section 5.2 we use the input of the inventory control policy to visualize the selected KPI(s). Finally, we validate the implemented KPI(s) with the coordinators. This is done by an evaluation with the coordinators if they can indeed effectively steer on product availability with the KPI(s).

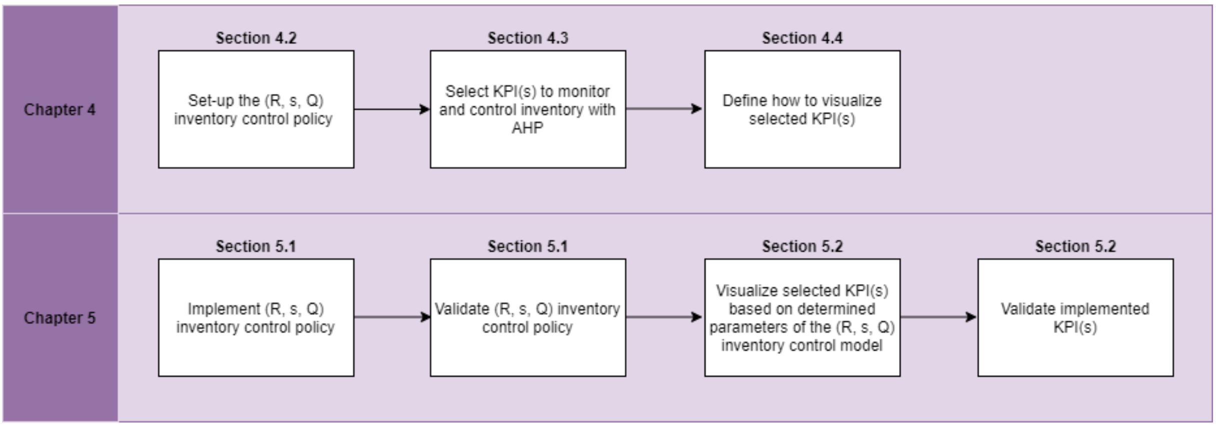

Figure 20 Flowchart of the solution design to increase product availability

4.2 Inventory control

The first step of the solution design is to set up the (R, s, Q) policy which will be worked with. The goal of the inventory control policy is to increase product availability. Therefore, we measure the performance of the inventory control policy by the increase of product availability. Product availability is defined as the time that green tyres are available for the curing openings, see Formula 1 in Section 1.5.1. The policy determines when to order, how much to order and how to buffer against supply uncertainties. To set up the (R, s, Q) policy for the green tyre inventory, we answer the two questions of Chopra & Meindl (2016) as stated in Section 3.1.2.

When to reorder?

To determine when to reorder, and thus the reorder level s, we use Formula 5 from Section 3.1.4. Therefore, we have to make decisions regarding the review period, safety inventory and safety lead time.

The green tyre inventory is currently revised every shift, see Section 2.2.2. The demand during a shift is frozen and the data in PIBS is updated at the end of a shift. The current production planning is thus based on a review period of one shift. Also, the decisions made by the coordinators as stated in Section 2.3.2 are made at the beginning of the shift based on the inventory levels. We want to be in line with the current production planning and to have the most updated inventory data to base the decisions of the coordinators on. Therefore, we choose to have a periodic review period of one shift.

Throughput of the curing openings can only be realized when there is a buffer. To buffer against uncertainties in an (R, s, Q) system, a safety inventory, a safety lead time or both can be introduced. We decide to use a safety lead time to buffer against supply uncertainties. A safety lead time makes the most sense when the essential uncertainty is in the production lead time according to Nahmias & Olsen (2015). Next, a safety lead time is in line with the definition of a buffer from TOC as stated in Section 1.2. It will be included in the reorder level. We do not have demand uncertainties, see Section 2.2.1. Therefore, no safety inventory will be introduced as this makes sense when the essential uncertainty is demand (Nahmias & Olsen, 2015).

The safety lead time is based on the time to produce a batch. The green tyres are delivered per rack as stated in Section 2.3, which is a partial delivery. Therefore, we define a batch as the time to produce one partial delivery. We assume for model simplification that only full racks are delivered. A full rack contains out of 18 or 24 green tyres, depending on the SKU. This division can be found in Appendix E. Next, we assume that there are no component shortages, so the lead time only includes one production level. This assumption is necessary because components are out of scope. This assumption can be made, as demand is known so there is no demand uncertainty and a safety lead time of two hours is maintained to cope with supply uncertainty of the components.

How much to reorder?
To determine the order quantity, we use the EPQ defined in Formula 3. To calculate the EPQ, we will use the demand per opening. We have 22 openings, but in practice there are always two openings in maintenance and not demanding. Therefore, we base our calculations on 20 demanding openings. We know the demand per opening, which is constantly 34 green tyres. However, the SKU assigned to an opening is not constant because mould changes in an opening are possible, see Section 2.2.1. A mould change is always planned after a multiple of 24 hours, so the demand per opening per SKU is known, constant and continuous for 24 hours. Therefore, we include the restriction that the order quantity per opening may not exceed the 24-hour demand. This constraint also suffices for the criteria that the green tyres perish after 48 hours, see Section 3.1.3. The 24-hour demand per SKU is thus always a multiple of the 24-hour demand per opening per SKU. Therefore, we reorder an amount of Q such that the inventory per SKU is raised to a value between s and s + Q (Janssen, Heuts, Kok, & T., 1996).

Next, we have to know the production rate for the EPQ, which is the green tyre supply per curing opening. We have 8 building machines supplying all 20 curing openings. Therefore, the supply and demand ratio of the green tyres is not one building machine to one curing opening. On average, we have $\frac{8\ building\ machines}{20\ curing\ openings} = 0.4$ building machine supplying one curing opening. This process is visualized in Figure 21, where p is the production rate and D the demand. We know the production rate per building machine per SKU. Therefore, to calculate the supply of one opening, we multiply the production rate per building machine with 0.4. We neglect the rebuilding time necessary when there is a change in SKU. This is done because there is no data available regarding the actual ratio, and thus how often we have to rebuild. In practice, a maximum of 5 SKUs are built and the SKU changes are minimized, see Section 2.2.2.1. Next, the setup costs included in the EPQ formula will account for these changes, so the retrieved value of the EPQ is valid.

Figure 21 Supply and demand per curing opening

4.3 KPI Selection

Having determined how to control the green tyre inventory, the KPI(s) can be selected. As the introduction of KPI(s) to monitor and control green tyre inventory is a goal and not an entire process, a maximum of three KPIs should be implemented. KPI selection should be in line with the stakeholders' criteria as stated in Section 2.4.1:

- It should give insight into qualitative inventory.
- It should be effective.

The KPI should thus give insight into qualitative inventory. Next, a KPI is effective when it suffices the following criteria: *Importance, Ease and Actionable.* The AHP method with the criteria *Importance, Ease and Actionable* as stated in Section 3.3.1 is used to select the KPIs. The proposed steps for this method are executed beneath.

Step 1: **Define and list all of the KPIs;**

As researched in Section 3.1.5, the following KPIs regarding inventory monitoring and control are defined and listed.

- Delivery in full, on-time rate
- Inventory shrinkage rate
- Products with more/less than a specified time period of inventory
- Fraction of time out of stock
- Product fill rate
- Cycle service level
- Stock cover per time unit
- Minimum/Maximum stock levels

Step 2: **Build an AHP hierarchy in which, the goal is to prioritize KPI alternatives with respect to the criteria: Importance, Ease and Actionable;**

Next, the AHP hierarchy can be found in Figure 22. The overall goal is the first criteria of the stakeholders, namely to define KPI(s) representing qualitative inventory. This is the first level of the diagram. The second level includes the criteria used to compare the KPI alternatives. Those criteria are based on the definition of effectiveness. The criteria to have an effective KPI is the second criteria of the stakeholders. Finally, the KPI alternatives are the third level as stated in the first step.

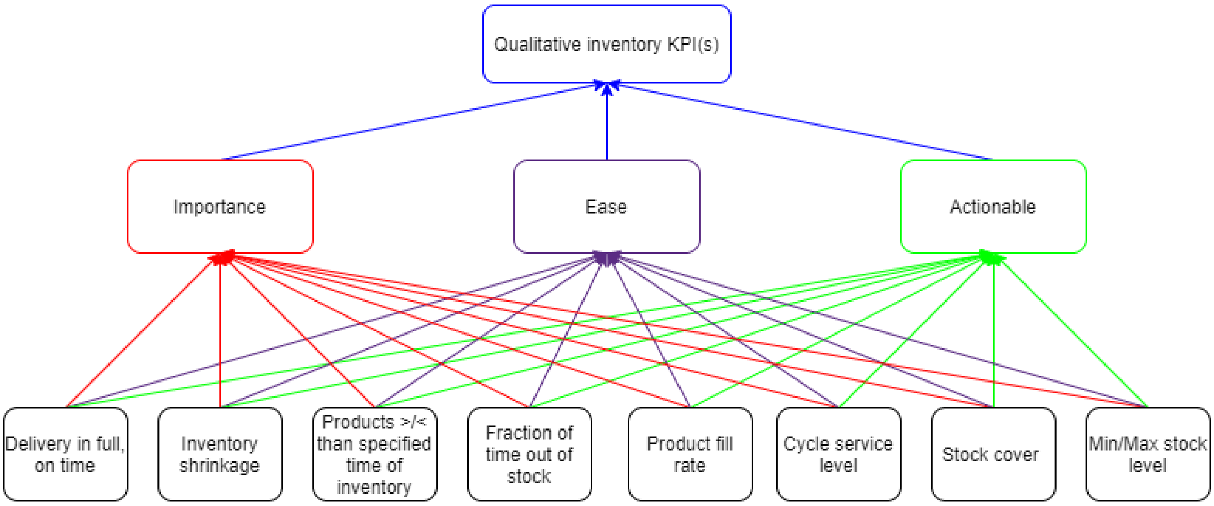

Figure 22 AHP hierarchy

Step 3: **Undertake a pairwise comparison between alternatives, i.e. KPIs;**
To undertake a pairwise comparison, we conduct a survey with the five coordinators. They are the main users of the to be defined KPI and thus the lower level kings according to TOC, see Section 2.4. They should embrace the importance of the implementation, so their opinion must be included. Next, their involvement is an objective of the Industrial Engineering Manager for the KPI implementation. The survey can be found in Appendix B.

In the survey, the coordinators are first asked to rank the criteria according to their importance and which degree of importance this is. Next, they are asked to rank the KPI alternatives according to their representation of the criteria.

Step 4: **Calculate composite priority: calculate local weights and global weights;**
The local and global weights are determined based on the survey results, which can be found in Appendix C. As the criteria are ranked pairwise by the coordinators, using the nine-point scale for AHP, the local weights are based on the equal importance of the coordinators. This scale is shown in Table 3. The ranking results of the KPIs are combined into final scores. Pairwise comparison is done by assigning the difference in points to a rating from the nine-point scale for AHP. This allocation and the pairwise comparisons can be found in Appendix C. The calculation of the local and global weights can be found in Appendix D.

Ratings	Definition	Intensity of importance
1	Equal importance	Two criteria/alternatives contribute equally to the objective
2	Weak	Experience and judgement slightly favour one criterion/alternative over another
3	Moderate importance	
4	Moderate plus	Experience and judgement strongly favour one criterion/alternative over another
5	Strong importance	
6	Strong plus	A criterion/alternative is favoured very strong over another
7	Very strong importance	
8	Very, very strong	The evidence favouring one criterion/alternative over another is of the highest possible order of affirmation
9	Extreme importance	

Table 3 The nine point scale of AHP analysis. Adapted from "Prioritization of Key Performance Indicators" (Shahin & Mahbod, 2007)

Step 5: **Selection of KPIs that are more relevant to organizational goals.**
We can select a maximum of 3 KPIs. This narrows the selection to stock cover, delivery in full on time and minimum/maximum stock level as shown in Table 4. Having the highest global weight, stock cover will be selected. Delivery in full on time will not be selected, as it would have the same purpose as stock cover including the quality of the delivered green tyres. The quality is already measured in KPIs related to another goal. Based on "less is better" as stated in Section 3.2.2, it would be double to present this again. Finally, a minimum and maximum stock level will be used. Within the stock cover KPI, both can be included as target situations. This will help the coordinators to steer the process and standardizes the levels of the inventory.

KPI	Global weight
Stock cover	7.12
Delivery in full on time	5.94
Minimum/maximum stock level	3.22
Inventory shrinkage	2.71
Products < specified time of inventory	2.38
Product fill rate	1.03
Out of stock	0.98
Cycle service level	0.62

Table 4 Global weights of the KPIs

4.4 KPI Visualization

Decided is to select the KPI stock cover with a standardized minimum and maximum level. As stock cover should be related to time to be in line with TOC, alert icons and traffic light icons are not useful. We do not want to indicate a trend of the inventory, but the coverage of the inventory compared to the demand. A trend icon is thus not the best fit. Gauges are a too complicated tool for this KPI. Inventory levels are not negative and using gauges means that there has to be a gauge for every SKU demanded. Generally speaking, the number of demanded SKUs will be around 5 as there will be a maximum of 5 SKUs cured. Based on less is better, 5 gauges are worse than one graph or bar.

The visualization used will be a progress bar. With a progress bar, the current green tyre inventory can be presented towards the demanded green tyres. We will indicate the current inventory level with a dot and exclude the regular used percentage. It will be excluded because a percentage is not in line with TOC. The time unit is, so we present the progress of the current inventory relative to the target levels per unit time. We define the target levels based on the parameters of the (R, s, Q) inventory control policy. The target levels including a minimum and maximum level are visualized by the use of colours. The colours used will be the colours of traffic lights, as it is a widely known symbol to communicate the state of inventory as stated in Section 3.2.4. Based on the colour in which the current inventory level is located, the coordinators will immediately know which SKUs are critical.

Next, we decided in Section 4.2 that the inventory is reviewed every shift. The decisions of the coordinators based on the KPI are also made every shift. Therefore, the KPI is reviewed frequently, so the labels used should be simple. The graph axis should start at zero and should have five steps. Size and position are not relevant as only one KPI is selected. Finally, we will look if the missing insights of the coordinators stated in Section 2.4 are still missing or if we need to include them as supporting analytics.

4.5 Conclusion

In this chapter, the solution design to increase product availability is discussed.

In Section 4.1, we presented a flowchart of the solution design.

Next, we explain in Section 4.2 that the purpose of the (R, s, Q) inventory control policy is to increase product availability. We set up the policy and choose to review every shift. We include the constraint that the order quantity should not exceed the 24-hour demand.

In Section 4.3 we selected the KPI stock cover with minimum and maximum inventory level to monitor and control the green tyre inventory. Selection was done through AHP with criteria importance, ease and actionable, based on the preferences of the coordinators.

Finally, in Section 4.4 the visualization of the KPI stock cover with minimum and maximum levels is chosen. A progress bar will be used to visualize the KPI. The colours used to indicate the target levels, including the minimum and maximum level, are the colours of a traffic light. Finally, we decide that the labels used in the visualization should be simple.

5. Implementation

In this chapter, we implement the solution design to increase product availability. In Section 5.1, we implement the inventory control policy to buffer against supply uncertainties. We validate the policy based on the downtime of historical data and conduct a sensitivity analysis. In Section 5.2 we implement the KPI such that the coordinators can effectively steer on the quality of the green tyre inventory. We visualize the KPI and we validate the KPI by evaluating with the coordinators if they can indeed effectively steer on product availability with this KPI. Finally, Section 5.3 gives a conclusion of the chapter.

5.1 Inventory control

We implement the inventory control policy (R, s, Q) with supply uncertainty. We explain the calculations by showing how the parameters are determined for SKU SM146020-G. The parameters of the other 24 SKUs are determined the same way. Those parameters and results are presented in Appendix E.

We first determine the order quantity and safety lead time if SKU SM146020-G is demanded by one opening. Next, we determine the reorder level per opening. We are not subject to a storage space capacity constraint, which we validate by the space-constraint based on Nahmias & Olsen (2015), see Section 3.1.4. We summarize the policy for SKU SM146020-G in Section 5.1.1.

Order quantity

We calculate the economic production quantity expressed in green tyres with Formula 3 as stated in Section 3.1.4. We define D, A, h, v and p the following:

$\boldsymbol{D}$: We define the demand D as the 24-hour demand per opening expressed in green tyres, see Section 4.2. The 8-hour demand of every opening regardless of the assigned SKU is 34 green tyres. This is the same for every opening regardless of which SKU it demands. Therefore, the 24-hour demand is:

$$D = 34 * 3 = 102 \; green \; tyres$$

$\boldsymbol{A}$: Orders costs A are defined as the setup time multiplied with machine costs per hour. The machine costs are €110,51 per hour and include the machine, labour and overhead costs. The setup time can be divided into two categories, an inch change which takes two hours or size change which takes half an hour. Based on historical data, 87.5% of the changes are inch changes and 12.5% are size changes. Therefore, the order costs are:

$$A = €110.51 * \big((87.5\% * 2) + (12.5\% * 0.5)\big) = €200.30.$$

$\boldsymbol{h}$: The annual holding costs h are 10% of the green tyre value v, which accounts for interest, space and risk costs. This gives us a 24-hour holding cost of:

$$h = \frac{10\% \; holdings \; costs \; per \; year}{365.25 \; days \; per \; year} = 0.027\%.$$

$\boldsymbol{v}$: The green tyre value v of SKU SM146020-G is €39.46.

$\boldsymbol{p}$: The production rate p is defined as the production rate of SKU SM146020-G for one opening in 24 hours. We exclude the 120 minutes break time. As stated in Section 4.2, we find this rate by multiplying the production rate per building machine with 0.4. The time to produce one green tyre of SKU SM146020-G (T_p) is 4.752 minutes. This gives a supply to the opening of:

$$p = 0.4 * \frac{1440\,\text{min} - 120\,\text{min}}{4.752\,\text{min}/GT} = 111\ green\ tyres$$

We put these values into the Formula of the EPQ and retrieve the following:

$$EPQ = \sqrt{\frac{2*200.30*102}{0.00027*39.46*(1-\frac{102}{111})}} = 6972\ green\ tyres$$

The EPQ of 6792 green tyres exceeds the 24-hour demand of 102 green tyres. The EPQ is high because we have high setup costs and low holding costs. Therefore, the order quantity will be equal to the 24-hour demand, so Q* = 102. Table 5 summarizes the parameters and results of the order quantity.

$\boldsymbol{D}(GT)$	$\boldsymbol{A}$ (€)	$\boldsymbol{h}$ (%)	$\boldsymbol{v}$ (€)	$\boldsymbol{T_p}$ (min)	$\boldsymbol{p_i}(GT)$	$\boldsymbol{EPQ}$ (GT)	$\boldsymbol{Q^*}(GT)$
102	200.30	0.027	39.46	4.752	111	6792	102

Table 5 Parameters and results of the EPQ

Safety lead time

To buffer against supply uncertainties, we implement a safety lead time expressed in hours. We calculate the safety lead time based on Formula 6 as stated in Section 3.1.4. We define z, T_{pb} and T_t as stated beneath.

$\boldsymbol{z}$ **:** To determine the safety factor, we first have to determine the CSL. In this case, CSL is the input of Apollo Vredestein. The green tyre availability measured over time should be ≥ 98% as stated in Section 1.5.1. Therefore, we take a CSL of 98%, which gives us a safety factor z of 2.05 (King, 2011, pp. 34, Figure 2), see Appendix F.

$\boldsymbol{T_{pb}}$**:** We define the production time as the time to produce a rack of green tyres because a rack is the delivery batch, see Section 4.2. A rack of SKU SM146020-G consists out of 24 green tyres and the time to produce one green tyre of SKU SM146020-G (T_p) is 4.752 minutes. Therefore, the time to produce a delivery batch is:

$$T_{pb} = 4.752 * 24 = 114.05\ minutes.$$

$\boldsymbol{T_t}$**:** The transport time is the time to bring a rack of green tyres to its location in inventory. According to measurements of Apollo Vredestein, this is 5.22 minutes and equal for all racks.

Based on this input, we retrieve the following formula for the safety lead time:

$$SLT = \frac{2.05 * (114.05 + 5.22)\ min}{60\ min} = 4.07\ hours$$

The green tyres should thus be available 4.07 hours before they will be cured. Table 6 summarizes the parameters and results of the safety lead time.

$\boldsymbol{CSL}$ (%)	$\boldsymbol{z}$	$\boldsymbol{Rack\ capacity}$ (GT)	$\boldsymbol{T_p}$ (min)	$\boldsymbol{T_{pb_i}}(min)$	$\boldsymbol{T_t}$ (min)	$\boldsymbol{SLT}$ (hr)
98	2.05	24	4.752	114.05	5.22	4.07

Table 6 Parameters and results of the SLT

Reorder level

The reorder level for SKU SM146020-G per opening is expressed in green tyres and determined with Formula 5 as stated in Section 3.1.4. We define D_{R+L} and SS the following:

$\boldsymbol{D_{R+SLT}}$: The review period is 8 hours and the safety lead time is 4.07 hours, so we are looking for the demand of 8 + 4.07 = 12.07 hours. The demand per 24 hours is 102 green tyres. Therefore:

$$D_{12.07\ hours} = \frac{102\ GT\ per\ 24\ hours}{24\ hours} * 12.07\ hours = 52\ green\ tyres.$$

$\boldsymbol{SS}$: We do not have safety inventory, see Section 4.2, so:

$$SS = 0$$

Therefore, we retrieve the following formula for the reorder level:

$$s = 52 + 0 = 52\ green\ tyres$$

The reorder level is thus equal to D_{R+L}.We reorder a multiple of 102 green tyres if the inventory position is lower than 52 green tyres. Table 7 summarizes the parameters and results of the reorder level.

$\boldsymbol{R}\ (hr)$	$\boldsymbol{SLT}\ (hr)$	$\boldsymbol{D}\ (GT)$	$\boldsymbol{s}\ (GT)$
8	4.07	102	52

Table 7 Parameters and results of the reorder level

Capacity validation

To validate that we are not subject to a storage space capacity constraint, we check if we have enough space to store the cycle inventory and safety lead time of the green tyres. We use the capacity constraint $\sum_{i=1}^{25} w_i Q_i(1-P_i) + w_i SLT_i \leq W$ adjusted from Nahmias & Olsen (2015) for this, see Section 3.1.4. W is defined as the total number of racks available, w_i as the space consumed of one green tyre on a rack, Q_i as the order quantity, P_i as the production ratio, see Section 3.1.4, and SLT_i as the safety lead time in green tyres.

However, the constraint determines the necessary capacity for 25 demanding curing openings and we have 20 demanding curing openings. Therefore, the 25 SKUs are not demanded at the same rate, so we have to determine a weighted average instead of a regular average. This is done based on the demand rate DR of the SKUs demanded from the 1st of January 2019 until the 31st of January 2020. This gives us the following constraint:

$$\frac{\sum_{i=1}^{25} DR_i * (w_i Q_i(1-P_i) + w_i SLT_i)}{\sum_{i=1}^{25} DR_i} * 20 \leq W.$$

W = 56 racks. The values per SKU of $DR_i\ (GT)$, $w_i\ (racks)$, $Q_i\ (GT), P_i$, $SLT_i\ (GT)$ are found in Appendix E. We get 1.89 * 20 = 38. Indeed, 38 ≤ 56, so we have enough space to store the green tyres on.

5.1.1 Summary of the (R, s, Q) policy

The most important findings of the (R, s, Q) model for the green tyre inventory per opening of SKU SM146020-G are summarized in Table 8. The parameters are expressed in hours (hr) and green tyres (GT). All input and determined parameters for the other 24 SKUs are determined with the same methodology and the results are found in Appendix E. The EPQ of every SKU exceeds the 24-hour demand of 102 green tyres. Therefore, the (R, s, Q) policy per opening for every SKU has parameters R = 8 hours and Q* = 102 green tyres.

$\boldsymbol{R}\ (hr)$	$\boldsymbol{EPQ}\ (GT)$	$\boldsymbol{Q}^{*}(GT)$	$\boldsymbol{SLT}\ (hr)$	$\boldsymbol{s}\ (GT)$
8	6792	102	4.07	52

Table 8 Summary of inventory control

5.1.2 Validation

To validate the proposed inventory control policy, we check based on historical data if the safety lead times will indeed increase product availability. We use the data of November 2019 until the end of February 2020, so we can compare the new NGT percentage to the old ones as stated in Section 1.5.1. We show both the NGT and the product availability, as the NGT is interesting for the Apollo Vredestein and the product availability is interesting for the industrial engineering perspective.

Currently, it is not possible within PIBS to define a safety lead time per SKU. Therefore, a weighted average of the safety lead time is determined based on the demand rate of the SKUs demanded between January 1st 2019 and January 31st 2020. DR_i and SLT_i are found in Appendix E. This results in a safety lead time of:

$$Average\ safety\ lead\ time = \frac{\sum_{i=1}^{25} DR_i * SLT_i}{\sum_{i=1}^{25} DR_i} = 3.14\ hours$$

To calculate the downtime when a safety lead time has been applied, the data should first be adjusted. We know from the historical data in which shift the downtime has taken place. However, we do not know from the historical data at which time the downtime has taken place. This does not matter when we calculate the total downtime because the necessary green tyres are not available. However, it does matter when we calculate the total downtime if a safety lead time has been applied.

Take the example when we know from historical data that we had a downtime of 50 minutes in shift X and a downtime of 100 minutes in shift X+1. Both downtimes are from the same curing opening and happened because the necessary green tyres were not available. The total downtime of shift X and shift X+1 was 50 + 100 = 150 minutes. However, we do not know if the downtime was one downtime of 150 minutes overlapping two shifts as shown in Figure 23 or that the downtimes of 50 and 100 minutes were independent from each other. In the first case, we should subtract the safety lead time once. In the second case, we should subtract the safety lead time twice. In agreement with Apollo Vredestein, we assume that if there is downtime in two succeeding shifts this is one downtime overlapping a change in shift as shown in Figure 23. Therefore, we should subtract the safety lead time once in this case.

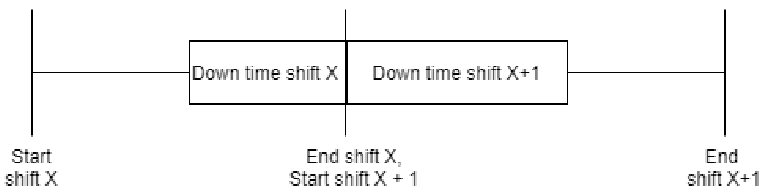

Figure 23 Overlapping down time in two shifts

We adjust the data and find with Formula 2 as stated in Section 1.5.1 that the inclusion of the safety lead time gives always less downtime and thus a lower NGT. Coherent to a lower NGT, it also results in a higher product availability, see Formula 1 in Section 1.5.1. Figure 24 shows the NGT with and without the inclusion of the safety lead time relative to the target level of 2%. Figure 25 shows the product availability before and after the inclusion of safety lead time relative to the target level of 98%. After the inclusion of the safety lead time, the average NGT is 1.3%, which is ≤ 2%. Coherent, the average product availability of 98.7%, which is ≥ 98%. The exact percentages per month are found in Appendix G. Therefore, this inclusion is valid.

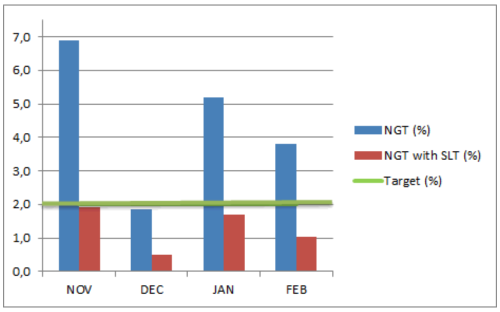

Figure 24 NGT with and without SLT relative to target level

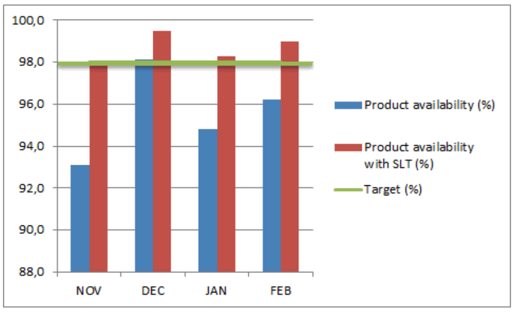

Figure 25 Product availability with and without SLT relative to target level

5.1.3 Sensitivity analysis

Next, we perform a sensitivity analysis to see how sensitive the product availability is to the assumed input parameters. The product availability is influenced by the safety lead time. We only have one assumed and thus uncertain parameter, which is the CSL. We used a CSL of 98% because that is the desired target level of Apollo Vredestein. This gave us an average product availability of 98.7% based on historical data. Therefore, we compare the product availability of different CSLs. We compare three values, 97%, 98% and 99%. We determine the product availability in the same ways as determined earlier this chapter. The results are shown in Table 9.

CSL (%)	z	Average SLT (hr)	Average product availability (%)
97	1.88	2.88	98.5
98	2.05	3.14	98.7
99	2.33	3.57	99.0

Table 9 Sensitivity analysis of CSL

We can see in Table 9 that an increase in CSL of 1%, increases the average product availability with 0.2% or 0.3%. This is because the green tyres are delivered per rack and there is downtime when we have to wait for a rack. Therefore, a time equal to at least the delivery time, $z \geq 1$, suffices for most downtimes. An increase in z when $z \geq 1$ means buffering for downtimes longer than the time to produce one rack, which indicates a longer, less frequent, temporary delay in production like a defect building machine. Therefore, increasing or decreasing the CSL with 1% has little effect on the product availability.

5.2 KPI visualization

Next, we implement the KPI stock cover with minimum and maximum inventory level. We decided to use a progress bar. In Figure 26, the black dot indicates the actual inventory level compared to three target levels. We indicate the target levels with the colours of the traffic light, where red is the minimum level, orange the intermediate level and green the maximum level, see Figure 26. We divide the three levels the following:

- **Red**
  This part will be everything ranging between zero and the minimum level. The minimum level is the safety lead time per SKU. When the current inventory is lower than the safety

lead time determined in Section 5.1, the product availability will be lower than 98%. If the planning is followed perfectly, the current inventory will never be in this part. Therefore, the quality of the inventory in this part is low.

- **Orange**
  This part will be everything ranging between the safety lead time and the end of the shift. The end of the shift is chosen because this is the review period based on the (R, s, Q) policy discussed in Section 4.2. If the current inventory is lower than the demand in the current shift and higher than the safety lead time, it means that the inventory is high enough to have a product availability of more than 98%. However, production in the current shift is still necessary to realize this, so the quality of the inventory is medium.

- **Green**
  This part will be everything ranging between the end of the current shift and the safety lead time of the following shift. This is based on the review period of one shift defined for the (R, s, Q) control policy used. This means that if the current inventory is in the green part, production is not necessary in the current shift. The quality of the inventory is high. It is also possible that the current inventory is even higher than the top level. This means that there is enough inventory to have a product availability of 98% in the next shift if there will not be produced in the current shift, but there will be produced in the next shift.

We use simple labels because the KPI is reviewed frequently. Therefore, we label only the name of the SKUs. We do not label the colours to keep it simple, because the traffic light is a widely recognized symbol of communicating a good, warning and bad state as stated in Section 3.2.4. We start the scale of the graph with 0. This resulted in the visualization of the KPI shown in Figure 26.

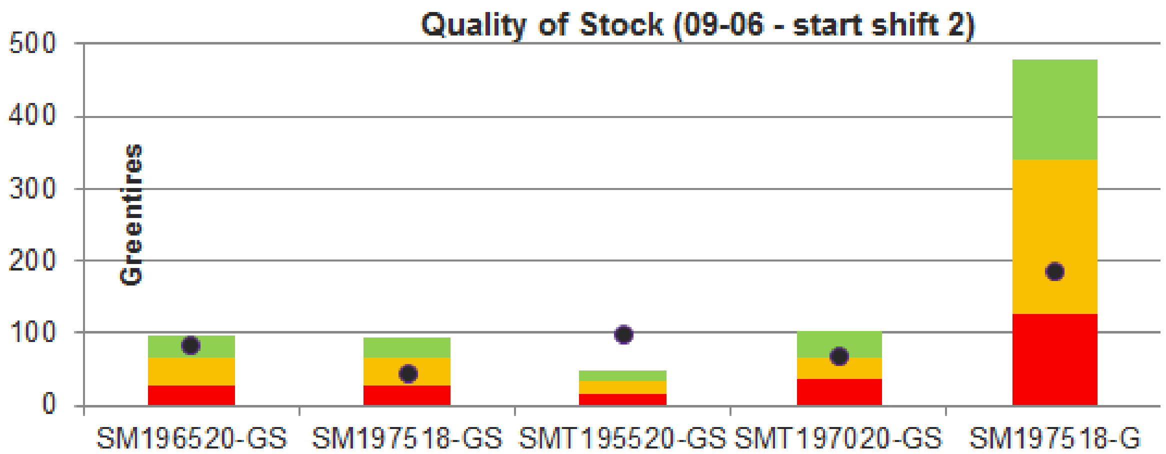

Figure 26 KPI visualization

Next, we look if the missing insights of the coordinators stated in Section 2.4 are still missing or if we need to include them as supporting analytics. The KPI indicates the actual inventory level at the start of the shift and it gives insight into the demand of the following shift. It does not give insight into the number of employees in the building and curing phases planned in future shifts, based on manning and machine capacity. Therefore, this will be included next to the KPI. The supporting analytic can be found in Appendix H.

5.2.1 Validation

To validate the chosen KPI and its visualization, an evaluation has been conducted with the coordinators. During the evaluation, we asked three questions based on the three criteria of effectiveness, namely importance, ease and actionable. The coordinators rated the questions on a scale from one to ten, where one is bad and ten is perfect. The questions and grades given per coordinator can be found in Appendix I. Based on equal importance of the coordinators and the local weights of the criteria calculated in Section 4.3, we determine an overall grade for the KPI. This information is summarized in Table 10. The KPI is effective when the overall grade is ≥ 6.0.

Criteria	Average grade	Local weight
Importance	8.6	0.76
Ease	9	0.56
Actionable	8.8	1.68

Table 10 Grades and local weights per criteria

This gives us an overall grade of:

$$Grade = \frac{(0.76*8.6)+(0.56*9)+(1.68*8.8)}{3} = 8.8$$

Indeed, 8.8 ≥ 6.0, so we can conclude that the KPI is effective to steer on the green tyre availability.

5.3 Conclusion

In this chapter, we implemented the solution design to increase product availability.

In Section 5.1, we implemented the (R, s, Q) inventory control policy with R = 8 hours, Q* =102 green tyres and with s as defined in Table 14 of Appendix E. We determined a safety lead time per SKU, which is included within the reorder level. We validated the increase of product availability with the weighted average safety lead time of 3.14 hours. We conducted a sensitivity analysis to see how sensible the product availability is based on the assumed CSL.

In Section 5.2, we visualized the KPI stock cover with minimum and maximum inventory level. We decided to define the minimum level as the safety lead time, the intermediate level as the demand of one shift and the maximum level as the safety lead time of the succeeding shift. Next, the supporting analytic *'the number of employees in the building and curing phase planned in future shifts'* will be added next to the KPI. An example can be found in Appendix H. The KPI has been visualized and validated during an evaluation with the coordinators, who graded the effectiveness of the KPI with an 8.8.

6. Conclusion and evaluation

In this chapter, the main research question will be answered in Section 6.1. Next, contributions to both practice and theory based on this research will be given in Section 6.2. Finally, we discuss the limitations of this research and suggestions for further research in Section 6.3.

6.1 Conclusion

To maximize the utilization of the curing presses because the green tyre availability is lower than 98%, we answer the main research question:

"How can we manage the green tyre inventory in the building phase of Space Master to improve green tyre availability in line with the Theory of Constraints?"

The green tyre inventory is identified as the bottleneck inventory and needs a suitable buffer according to the Theory of Constraints. To manage this inventory, an (R, s, Q) inventory control policy can be introduced with R = one shift, Q = 102 green tyres and s defined per SKU, see Appendix E for those values. The reorder level includes the safety lead time. This policy buffers against supply uncertainties with the included safety lead time of 3.14 hours in the reorder level. The introduction of a safety lead time contributes to the Theory of Constraints. Based on historical data, this policy suffices a product availability of ≥ 98% and an idle time of the curing presses because there is no matching inventory available of ≤ 2%.

Next, the KPI stock cover with minimum and maximum inventory levels can be introduced such that the coordinators can monitor and control the green tyre inventory. The minimum level chosen is the safety lead time identified from the (R, s, Q) policy. Based on the review period of one shift, the maximum level is the safety lead time of the succeeding shift. The KPI has been evaluated to be effective for steering on green tyre availability. With this KPI, the coordinators are aware of deviations. Next, they know what the green tyre output should be to suffice throughput of the curing openings and how to steer on better product availability.

6.2 Contribution to practice and theory

In this section, we discuss the contribution of this research to both practice and theory.

Contribution to practice

In order to realize the conclusions stated in Section 6.1, we recommend the following to Apollo Vredestein:

- To improve the green tyre availability, we recommend implementing an (R, s, Q) inventory control policy as described in Section 5.1. All parameters can be introduced within PIBS without any big investments. The order quantities should be adjusted to 102 green tyres for every SKU. The parameter transport time within PIBS can be seen as a safety lead time and should be adjusted to 3.14 hours. The reorder level in PIBS should include this proposed safety lead time.
- To improve the green tyre availability, we implemented the KPI stock cover with a minimum and maximum inventory level as visualized in Section 5.2. We included this to the daily report, which the coordinators get at the start of their shift. Therefore, we recommend them to use this KPI to steer on the quality of the green tyre inventory. The daily report with the new KPI can be found in Appendix J.
- To support the introduced KPI, we implemented the supporting analytic '*Number of employees in the building and curing phase planned in succeeding shifts*'. This implementation is done in the daily report. The coordinators already reported manually in

this report the net staffing of the following shifts in a table. Therefore, we expanded this table in the daily report with two extra columns, labelled *'From which in the building phase'* and *'From which in curing phase'*. We recommend the coordinators to also report the numbers belonging to these columns. The supporting analytic in English can be found in Appendix H. The daily report with the new supporting analytic can be found in Appendix J.

- To make steering on the KPIs effective, the input data should be accurate as stated in Section 3.2.1. To make the data more accurate, first we recommend to exclude the building machine storage from the green tyre inventory tracked within PIBS. This way, decisions based on inventory are based on the available inventory for curing.
- Second, to make the data more accurate, we recommend to use the scanning system to track the SM green tyre inventory within PIBS. This system is used within PCT as discussed in Section 2.3.3. This implementation does not require big changes. During transport, the racks are already scanned when picked up and delivered. Therefore, to implement this the parameter in PIBS '*Calculating with GLS inventory*' should be adjusted to '*YES*'. Next, an introduction and explanation of the system to the users is necessary. This also increases the available production time, as no operator needs to count the current inventory anymore at the begin of the shift.

Contribution to theory

Although we conducted a case study for Apollo Vredestein, we also retrieved some findings useful to literature. This research has achieved a successful implementation of inventory control in an MRP system in line with the Theory of Constraints. This combination is discussed a little to none in literature. Therefore, the methodology used can be interesting for other researches in an MRP system without demand uncertainties.

- To start with, Axäster (2015) describes MRP as a reorder point system, where the reorder points are updated continuously with respect to known discrete requirements. However, this is only true when continuous review is possible. We found in our research that we can use an inventory control policy with periodic review in an MRP system if the demand during a multiple of the review period is known, constant and continuous. In this case, MRP is essentially a reorder point system, where the reorder points are updated every review period with respect to known discrete requirements.
- Next, often is buffered in MRP systems with safety inventory. However, we recommend to buffer with a safety lead time because there is no demand uncertainty. A safety lead time is also in line in a make-to-order environment like TOC suggests, because every product in the system is ordered. The relation between safety lead time and an inventory control policy is often not stated explicitly in literature. We found that the inclusion of safety lead time influences the reorder level. When there is periodic review and no safety inventory, the reorder level is equal to the demand during the review period and the safety lead time as stated in Section 3.1.4.
- Finally, we extended the capacity constraint from Nahmias & Olsen (2015) because it did not take into account a finite production rate and the capacity necessary for the safety lead time. Therefore, we recommend to use this constraint as stated in Section 3.1.4 to check if there is enough capacity in an MRP system with a finite production rate and with a safety lead time.

6.3 Limitations and further research

This research includes some limitations. We discuss the limitations and suggest Apollo Vredestein the following for further research to overcome these limitations:

- The first limitation we had is the current information technology system PIBS. It is not possible yet to implement a safety lead time per SKU. Therefore, we determined a weighted average of the safety lead time and recommended to implement this in PIBS. This value is not the most accurate, as it is based on a historic demand rate, which is not necessarily the same as or comparable to the future demand rate. However, an updated version of PIBS is in development at the moment. Therefore, to increase the inventory control accuracy, we recommend researching the possibility to implement a safety lead time per SKU in PIBS.
- The second limitation we encountered was the available time. Therefore, we had to scope our research. As a consequence, the green tyre order quantity determined only optimizes the building and curing phase. However, a green tyre consists out of several components. The ratios of the components relative to each other and the components relative to an order quantity were not included. Next, factors like scrap, potential to rework the material and costs of a component should also be taken into account. Therefore, to obtain an order quantity which optimizes the entire production process, we suggest further research.
- Next, also because of limited time and because of limited data availability, we divided the building machines supplying the curing openings equally. This division gives a good indication as it averages the outliers, but it can be more accurate. In practice, it happens that sometimes one building machine supplies one curing opening. This has an influence on the production rate and thus on the optimal order quantity, cycle inventory and capacity. Therefore, to increase the inventory control accuracy, we suggest to research division of the building machines per curing opening per SKU, and thus the accurate production rate per curing opening per SKU.
- Again because of limited time, we based the division between inch and size change on a historic dataset of 40 days. In agreement with Apollo Vredestein, this is number is sufficient for a proper indication. However, to get a more reliable division we recommend further research towards this division with a bigger dataset.
- Another limitation is that this research has been conducted during the period in which we experienced Covid-19 and an announcement for a reorganisation of Apollo Vredestein. This influenced the data and motivation of employees. For the quantitative data, we took the data from before March 2020 to still have reliable results. However, the reliability of the qualitative data is threatened. Qualitative data is used mainly for KPI selection and KPI validation. Both are based on opinions of the coordinators and therefore we recommend to validate the implementation of the KPI again. We suggest to validate this regularly, e.g. monthly, because it is unknown when the influences of both COVID-19 and the announced reorganisation are gone. Validating regularly also gives the possibility to improve the KPI based on experience. We suggest to validate the same way as described in Section 5.2.1. Next, we suggest to evaluate the KPI on its completeness and expand it when necessary.
- Finally, we suggest to research the other two core problems which we can influence as stated in Section 1.5.1. The first one is to research adjusted production norms when a change of SKU is included. Steering on the KPIs is more effective when the input data of a KPI is realistic, see Section 3.2.1. However, the production norm, which is the input of the KPI, is currently not realistic when a change of SKU is included. Therefore, we recommend to research adjusted production norms. The second one is to research the unaccountable downtime of the curing presses. This is also a core problem and can only be improved when is accounted for this downtime. Improvement in this downtime also improves systemwide throughput of the plant, so we recommend to research the unaccountable downtime and how to improve it.

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Appendix

Appendix A: Building production planning

We converted the original building production planning. We did this because the original one is in Dutch and to put it in an industrial engineering perspective. To convert this, we used the original building production planning in Figure 27.

JOHNNY SM 143 HANDMATIG PLANNEN BOUWMACHINE 12/03/20 12:01
Datum 12/03/20 Dienst 2 Wijzigen
Mach: 43

	D	D+1	D+2	D+3	D+4	D+5	
Maat: SM197518-G	D	D+1	D+2	D+3	D+4	D+5	
Begin-voorraad:	32	53	74	95	116	137	
Vulk. gepland :	68	68	68	68	68	68	
1 Order 738 :	63	0	0	0	0	0	PRD
Maat: SM197518-G	D	D+1	D+2	D+3	D+4	D+5	
Begin-voorraad:	32	53	74	95	116	137	
Vulk. gepland :	68	68	68	68	68	68	
2 Order 739 :	26	64	0	0	0	0	BST
Maat: SM197518-G	D	D+1	D+2	D+3	D+4	D+5	
Begin-voorraad:	32	53	74	95	116	137	
Vulk. gepland :	68	68	68	68	68	68	
3 Order 740 :	0	25	65	0	0	0	BST
Maat: SM197518-G	D	D+1	D+2	D+3	D+4	D+5	
Begin-voorraad:	32	53	74	95	116	137	
Vulk. gepland :	68	68	68	68	68	68	
4 Order 741 :	0	0	24	66	0	0	BST
Totaal gepland :	89	89	89	89	89	89	Maten: 1

Figure 27 Original building production planning

Appendix B: Survey

A survey has been conducted to rank the criteria and KPIs pairwise. In the first two questions, the coordinators have to rank the importance of the effectiveness criteria and compare them pairwise. In the next three questions, the coordinators are asked to rank the KPI(s) based on their representation of a criteria. Since pairwise comparison is too time-consuming with 8 KPIs, the ranking assigns points to a KPI. If a KPI has been ranked first, it receives 8 points. A second-place receives 7 points, a third-place 6 points etc. and the last place receives one point. Each coordinator assigns the same number of points, so in case all coordinators rank the same KPI first it receives 40 points. The survey has been conducted in Dutch and has been translated into English for the purpose of this report.

Information consult

Dear Coordinator,

During the meetings it came forward that a huge part of your responsibilities consists out of balancing the building phase and the curing phase. To make this easier, I am going to implement indicators, the so-called KPI(s) (Key Performance Indicators). With the use of this KPI(s), we hope to improve the throughput of the plant which is in connection with TOC (Theory of Constraints). Since you have the most knowledge regarding the steering of the building phase and the curing phase based on the inventory, I need your help for KPI selection!

The KPI(s) are related to the quality of the inventory green tyres per SKU of Space Master. To make sure that the KPI(s) are also effective, effectively is divided into the following three criteria:

Importance: Do we measure the quality of the inventory?
Ease: Does the quality of inventory directly flow from the KPI?
Actionable: Do we know by seeing the KPI how to improve the inventory?

The first two questions will be related to the three criteria and how important you think these criteria are. The following three questions are related to how well the KPIs represent a criterium.

The survey consists of 5 questions and will take a maximum of 10 minutes. The survey is completely anonymous. Participation of the survey is voluntary and you have the right to withdraw your participation at all times for any reason. By starting the survey, you confirm that you are aware of this.

Many thanks already for your participation!

Question 1: Which criteria of an effective KPI is the most important?
Rank the criteria based on your opinion. (1. – Most important, 3 – Least important)

1. Importance: Do we measure the quality of the inventory?
2. Ease: Does the quality of inventory directly flow from the KPI?
3. Actionable: Do we know by seeing the KPI how to improve the inventory?

Question 2: How much more important are the criteria you ranked in question 1?
`1 = Equal importance, 3 = Moderate importance, 5 = Strong importance, 7 = Very strong importance, 9 = Extreme importance

	1	2	3	4	5	6	7	8	9
Rank 1 compared to rank 2:									
Rank 1 compared to rank 3:									

Rank 2 compared to rank 3:									

Question 3: How well represent the following indicators the importance (do we measure the quality of the inventory?)?
Rank the indicators based on your opinion. (1. – The best, 8. – The worst)

1. Delivery in full on time = The number of good quality green tyres delivered on time compared to the total number of cured green tyres
2. Stock cover = Current inventory green tyres compared to the necessary green tyres in the curing phase
3. Minimum / maximum inventory level of the green tyres
4. Inventory shrinkage = Difference between the planned and current inventory compared to the planned inventory
5. Green tyres with less than a specified time inventory
6. Out of stock = Time per green tyre without stock compared to the total time
7. Fill rate = Green tyres used from inventory to satisfy the curing phase compared to the green tyres which were necessary in the curing phase
8. Service level = Time the curing phase could cure without having NGT

Question 4: How well represent the following indicators the ease (does the quality of inventory directly flow from the KPI?)?
Rank the indicators based on your opinion. (1. – The best, 8. – The worst)

1. Delivery in full on time = The number of good quality green tyres delivered on time compared to the total number of cured green tyres
2. Stock cover = Current inventory green tyres compared to the necessary green tyres in the curing phase
3. Minimum / maximum inventory level of the green tyres
4. Inventory shrinkage = Difference between the planned and current inventory compared to the planned inventory
5. Green tyres with less than a specified time inventory
6. Out of stock = Time per green tyre without stock compared to the total time
7. Fill rate = Green tyres used from inventory to satisfy the curing phase compared to the green tyres which were necessary in the curing phase
8. Service level = Time the curing phase could cure without having NGT

Question 5: How well represent the following indicators the actionability (do we know by seeing the KPI how to improve the inventory?)?
Rank the indicators based on your opinion. (1. – The best, 8. – The worst)

1. Delivery in full on time = The number of good quality green tyres delivered on time compared to the total number of cured green tyres
2. Stock cover = Current inventory green tyres compared to the necessary green tyres in the curing phase
3. Minimum / maximum inventory level of the green tyres
4. Inventory shrinkage = Difference between the planned and current inventory compared to the planned inventory
5. Green tyres with less than a specified time inventory
6. Out of stock = Time per green tyre without stock compared to the total time
7. Fill rate = Green tyres used from inventory to satisfy the curing phase compared to the green tyres which were necessary in the curing phase
8. Service level = Time the curing phase could cure without having NGT

Appendix C: Survey results and pairwise comparison

In the first two questions, the criteria are already ranked pairwise by the coordinators. In the following three questions the coordinators are asked to rank the KPI(s) based on their representation of a criteria. Since pairwise comparison is too time-consuming with 8 KPIs, the ranking assigns points to a KPI. If a KPI has been ranked first, it receives 8 points. A second-place receives 7 points, a third-place 6 points etc. and the last place receives one point. Each coordinator assigns the same number of points, so in case all coordinators rank the same KPI last it receives 5 points. This is done for the representation of *Actionable* by the KPI *Cycle Service Level* as shown in Figure 28. The results of the survey are found in Figure 28.

Pairwise comparision per coordinator			
Coordinator 1	Importance	Ease	Actionable
Importance	1.00	6.00	0.13
Ease	0.17	1.00	0.14
Actionable	8.00	7.00	1.00
Total	*9.17*	*14.00*	*1.27*
Coordinator 2	Importance	Ease	Actionable
Importance	1.00	0.20	0.20
Ease	5.00	1.00	0.20
Actionable	5.00	5.00	1.00
Total	*11.00*	*6.20*	*1.40*
Coordinator 3	Importance	Ease	Actionable
Importance	1.00	3.00	7.00
Ease	0.33	1.00	3.00
Actionable	0.14	0.33	1.00
Total	*1.48*	*4.33*	*11.00*
Coordinator 4	Importance	Ease	Actionable
Importance	1.00	6.00	0.13
Ease	0.17	1.00	0.14
Actionable	8.00	7.00	1.00
Total	*9.17*	*14.00*	*1.27*
Coordinator 5	Importance	Ease	Actionable
Importance	1.00	0.20	0.20
Ease	5.00	1.00	0.33
Actionable	5.00	3.00	1.00
Total	*11.00*	*4.20*	*1.53*

Ranking of the KPIs	
Importance	**Points ranked**
Delivery in full on time	35
Stock cover	35
Min/Max stock level	29
Inventory shrinkage	25
Product Fill Rate	16
Products < specified time inventory	14
Out of stock	13
Cycle Service Level	13
Ease	**Points ranked**
Stock cover	37
Delivery in full on time	34
Inventory shrinkage	27
Products < specified time inventory	25
Min/Max stock level	22
Out of stock	16
Product Fill Rate	10
Cycle Service Level	9
Actionable	**Points ranked**
Stock cover	36
Delivery in full on time	35
Min/Max stock level	27
Products < specified time inventory	26
Inventory shrinkage	25
Out of stock	13
Product Fill Rate	13
Cycle Service Level	5

Figure 28 Survey results

Next, based on the AHP rating scale, the difference in points is assigned to a rating as shown in Table 11. The pairwise comparison can be found in Figure 29.

Difference in points	Rating	Definition	Intensity of importance
0	1	Equal Importance	Two criteria/alternatives contribute equally to the objective
1-5	2	Weak	Experience and judgement slightly favour one criterion/alternative over another
6-10	3	Moderate importance	
11-15	4	Moderate plus	Experience and judgement strongly favour one criterion/alternative over another
16-20	5	Strong importance	
21-25	6	Strong plus	A criterion/alternative is favoured very strong over another
26-30	7	Very strong importance	
31-35	8	Very, very strong	The evidence favouring one criterion/alternative over another is of the highest possible order of affirmation
36-40	9	Extreme importance	

Table 11 Rating scale Based on "Prioritization of Key Performance Indicators" (Shahin & Mahbod, 2007)

Importance	Delivery in full on time	Stock cover	Min/Max stock level	nventory shrinkage	Products < specified time inventory	Out of stock	Product Fill Rate	Cycle Service Level
Delivery in full on time	1.00	1.00	3.00	3.00	6.00	6.00	5.00	6.00
Stock cover	1.00	1.00	3.00	3.00	6.00	6.00	5.00	6.00
Min/Max stock level	0.33	0.33	1.00	2.00	4.00	5.00	4.00	5.00
Inventory shrinkage	0.33	0.33	0.50	1.00	4.00	4.00	4.00	4.00
Products < specified time inventory	0.17	0.17	0.25	0.25	1.00	2.00	0.50	2.00
Out of stock	0.17	0.17	0.20	0.25	0.50	1.00	0.50	1.00
Product Fill Rate	0.20	0.20	0.25	0.25	2.00	2.00	1.00	2.00
Cycle Service Level	0.17	0.17	0.20	0.25	0.50	1.00	0.50	1.00
Total	**3.37**	**3.37**	**8.40**	**10.00**	**24.00**	**27.00**	**20.50**	**27.00**

Ease	Delivery in full on time	Stock cover	Min/Max stock level	nventory shrinkage	Products < specified time inventory	Out of stock	Product Fill Rate	Cycle Service Level
Delivery in full on time	1.00	0.50	4.00	3.00	3.00	5.00	6.00	6.00
Stock cover	2.00	1.00	4.00	3.00	4.00	6.00	7.00	7.00
Min/Max stock level	0.25	0.25	1.00	0.50	0.50	3.00	4.00	4.00
Inventory shrinkage	0.33	0.33	2.00	1.00	2.00	4.00	5.00	5.00
Products < specified time inventory	0.33	0.25	2.00	0.50	1.00	3.00	4.00	5.00
Out of stock	0.20	0.17	0.33	0.25	0.33	1.00	3.00	3.00
Product Fill Rate	0.17	0.14	0.25	0.20	0.25	0.33	1.00	2.00
Cycle Service Level	0.17	0.14	0.25	0.20	0.20	0.33	0.50	1.00
Total	**4.45**	**2.79**	**13.83**	**8.65**	**11.28**	**22.67**	**30.50**	**33.00**

Actionable	Delivery in full on time	Stock cover	Min/Max stock level	nventory shrinkage	Products < specified time inventory	Out of stock	Product Fill Rate	Cycle Service Level
Delivery in full on time	1.00	0.50	3.00	3.00	3.00	6.00	6.00	7.00
Stock cover	2.00	1.00	3.00	4.00	3.00	6.00	6.00	8.00
Min/Max stock level	0.33	0.33	1.00	2.00	2.00	4.00	4.00	6.00
Inventory shrinkage	0.33	0.25	0.50	1.00	0.50	4.00	4.00	5.00
Products < specified time inventory	0.33	0.33	0.50	2.00	1.00	4.00	4.00	6.00
Out of stock	0.17	0.17	0.25	0.25	0.25	1.00	1.00	3.00
Product Fill Rate	0.17	0.17	0.25	0.25	0.25	1.00	1.00	3.00
Cycle Service Level	0.14	0.13	0.17	0.20	0.17	0.33	0.33	1.00
Total	**4.48**	**2.88**	**8.67**	**12.70**	**10.17**	**26.33**	**26.33**	**39.00**

Figure 29 Pairwise comparison of the KPIs

Appendix D: Calculations of local and global weights

To calculate the local weights of both the criteria and KPIs, the pairwise comparison should be normalized. The normalized comparison of the KPIs and criteria can be found in respectively Figure 30 and 31. Next, the local weights are calculated for the criteria used. Those calculations are shown in Figure 32. Finally, the global weights of the KPIs are determined, which are found in Figure 33.

Importance	Delivery in full on time	Stock cover	Min/Max stock level	Inventory shrinkage	Products < specified time inventory	Out of stock	Product Fill Rate	Cycle Service Level	**Total**
Delivery in full on time	0.30	0.30	0.36	0.30	0.25	0.22	0.24	0.22	**2.19**
Stock cover	0.30	0.30	0.36	0.30	0.25	0.22	0.24	0.22	**2.19**
Min/Max stock level	0.10	0.10	0.12	0.20	0.17	0.19	0.20	0.19	**1.25**
Inventory shrinkage	0.10	0.10	0.06	0.10	0.17	0.15	0.20	0.15	**1.02**
Products < specified time inventory	0.05	0.05	0.03	0.03	0.04	0.07	0.02	0.07	**0.37**
Out of stock	0.05	0.05	0.02	0.03	0.02	0.04	0.02	0.04	**0.27**
Product Fill Rate	0.06	0.06	0.03	0.03	0.08	0.07	0.05	0.07	**0.45**
Cycle Service Level	0.05	0.05	0.02	0.03	0.02	0.04	0.02	0.04	**0.27**
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

Ease	Delivery in full on time	Stock cover	Min/Max stock level	Inventory shrinkage	Products < specified time inventory	Out of stock	Product Fill Rate	Cycle Service Level	**Total**
Delivery in full on time	0.22	0.18	0.29	0.35	0.27	0.22	0.20	0.18	**1.91**
Stock cover	0.45	0.36	0.29	0.35	0.35	0.26	0.23	0.21	**2.51**
Min/Max stock level	0.06	0.09	0.07	0.06	0.04	0.13	0.13	0.12	**0.71**
Inventory shrinkage	0.07	0.12	0.14	0.12	0.18	0.18	0.16	0.15	**1.12**
Products < specified time inventory	0.07	0.09	0.14	0.06	0.09	0.13	0.13	0.15	**0.87**
Out of stock	0.04	0.06	0.02	0.03	0.03	0.04	0.10	0.09	**0.42**
Product Fill Rate	0.04	0.05	0.02	0.02	0.02	0.01	0.03	0.06	**0.26**
Cycle Service Level	0.04	0.05	0.02	0.02	0.02	0.01	0.02	0.03	**0.21**
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

Actionable	Delivery in full on time	Stock cover	Min/Max stock level	Inventory shrinkage	Products < specified time inventory	Out of stock	Product Fill Rate	Cycle Service Level	**Total**
Delivery in full on time	0.22	0.17	0.35	0.24	0.30	0.23	0.23	0.18	**1.91**
Stock cover	0.45	0.35	0.35	0.31	0.30	0.23	0.23	0.21	**2.41**
Min/Max stock level	0.07	0.12	0.12	0.16	0.20	0.15	0.15	0.15	**1.12**
Inventory shrinkage	0.07	0.09	0.06	0.08	0.05	0.15	0.15	0.13	**0.78**
Products < specified time inventory	0.07	0.12	0.06	0.16	0.10	0.15	0.15	0.15	**0.96**
Out of stock	0.04	0.06	0.03	0.02	0.02	0.04	0.04	0.08	**0.32**
Product Fill Rate	0.04	0.06	0.03	0.02	0.02	0.04	0.04	0.08	**0.32**
Cycle Service Level	0.03	0.04	0.02	0.02	0.02	0.01	0.01	0.03	**0.18**
Total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	8.00

Figure 30 Normalized pair wise comparison of the KPIs

Normalized pair wise comparision criteria				
Coordinator 1	Importance	Ease	Actionabl	**Total**
Importance	0.11	0.43	0.10	**0.64**
Ease	0.02	0.07	0.11	**0.20**
Actionable	0.87	0.50	0.79	**2.16**
Total	*1.00*	*1.00*	*1.00*	**3.00**
Coordinator 2	Importance	Ease	Actionable	
Importance	0.09	0.03	0.14	**0.27**
Ease	0.45	0.16	0.14	**0.76**
Actionable	0.45	0.81	0.71	**1.98**
Total	*1.00*	*1.00*	*1.00*	**3.00**
Coordinator 3	Importance	Ease	Actionable	
Importance	0.68	0.69	0.64	**2.01**
Ease	0.23	0.23	0.27	**0.73**
Actionable	0.10	0.08	0.09	**0.26**
Total	*1.00*	*1.00*	*1.00*	**3.00**
Coordinator 4	Importance	Ease	Actionable	
Importance	0.11	0.43	0.10	**0.64**
Ease	0.02	0.07	0.11	**0.20**
Actionable	0.87	0.50	0.79	**2.16**
Total	*1.00*	*1.00*	*1.00*	**3.00**
Coordinator 5	Importance	Ease	Actionable	
Importance	0.09	0.05	0.13	**0.27**
Ease	0.45	0.24	0.22	**0.91**
Actionable	0.45	0.71	0.65	**1.82**
Total	*1.00*	*1.00*	*1.00*	**3.00**

Figure 31 Normalized pair wise comparison of the criteria

Criteria	Local weight
Importance	0.76
Ease	0.56
Actionable	1.68
Total	*3.00*

Importance	Local weight
Delivery in full on time	2.19
Stock cover	2.19
Min/Max stock level	1.25
Inventory shrinkage	1.02
Products < specified time inventor	0.37
Out of stock	0.27
Product Fill Rate	0.45
Cycle Service Level	0.27
Total	*8.00*

Ease	Average
Delivery in full on time	1.91
Stock cover	2.51
Min/Max stock level	0.71
Inventory shrinkage	1.12
Products < specified time inventor	0.87
Out of stock	0.42
Product Fill Rate	0.26
Cycle Service Level	0.21
Total	*8.00*

Actionable	Average
Delivery in full on time	1.91
Stock cover	2.41
Min/Max stock level	1.12
Inventory shrinkage	0.78
Products < specified time inventor	0.96
Out of stock	0.32
Product Fill Rate	0.32
Cycle Service Level	0.18
Total	*8.00*

Figure 32 Local weights of the criteria and KPIs

KPI	Global weight
Stock cover	7.12
Delivery in full on time	5.94
Min/Max stock level	3.22
Inventory shrinkage	2.71
Products < specified time inventor	2.38
Product Fill Rate	1.03
Out of stock	0.98
Cycle Service Level	0.62

Figure 33 Global weights of the KPIs

Appendix E: Inventory control policy values per SKU

First, we summarize the input values independent of SKU in Table 12. Those are necessary to determine the parameters and the same as used in the example in Section 5.1.

$\boldsymbol{R}(hr)$	$\boldsymbol{A}$ (€)	$\boldsymbol{h}$ (%)	$\boldsymbol{CSL}$ (%)	$\boldsymbol{Z}$	$\boldsymbol{T_t}(min)$	$\boldsymbol{D}(GT)$
8	200.30	0.027	98	2.05	5.22	102

Table 12 Inventory control values independent of SKU

Next, in Table 13 we summarize the values per SKU for the order quantities.

$\boldsymbol{SKU}$	$\boldsymbol{V}$(€)	$\boldsymbol{T_p}$ (min)	$\boldsymbol{p}(GT)$	$\boldsymbol{EPQ}$ (GT)	$\boldsymbol{Q}^*(GT)$
SM146020-G	39.46	4.752	111	6792	102
SM147017-G	31.53	4.460	118	5850	102
SM167016-G	29.33	4.363	121	5692	102
SM168017-G	32.62	4.460	118	5752	102
SM175019-G	36.11	4.655	113	6405	102
SM175518-G	33.25	4.558	116	6128	102
SM175519-G	34.25	4.655	113	6576	102
SM175519-GS	35.79	4.655	113	6433	102
SM185520-G	38.75	4.752	111	6854	102
SM185520-GS	41.70	4.752	111	6607	102
SM186017-G	33.75	4.460	118	5654	102
SM186519-G	35.34	4.655	113	6474	102
SM187517-G	33.86	4.460	118	5645	102
SM195020-GS	37.30	4.752	111	6986	102
SM195520-G	38.94	4.752	111	6837	102
SM196519-G	38.17	4.655	113	6229	102
SM196520-GS	42.42	4.752	111	6551	102
SMT197020-GS	40.34	4.655	111	6717	102
SM197518-G	36.74	4.558	116	5830	102
SM197518-GS	39.47	4.558	116	5624	102
SM198017-G	36.05	4.460	118	5471	102
SM207016-G	33.66	4.363	121	5313	102
SMT196521-GS	47.05	4.849	109	7084	102
SMT195520-GS	44.98	4.363	111	6362	102
SMT187019-GS	42.25	4.363	113	5921	102

Table 13 Inventory control values for the order quantity

In Table 14, we summarize the values per SKU for the safety lead times.

$\boldsymbol{SKU}$	$\boldsymbol{Rack\ capacity}$ (GT)	$\boldsymbol{T_p}$ (min)	$\boldsymbol{T_{pb_i}}(min)$	$\boldsymbol{SLT}$ (hr)
SM146020-G	24	4.752	114.05	4.07
SM147017-G	24	4.460	107.05	3.84
SM167016-G	24	4.363	104.72	3.76
SM168017-G	18	4.460	80.29	2.92
SM175019-G	24	4.655	111.72	4.00
SM175518-G	24	4.558	109.38	3.92
SM175519-G	24	4.655	111.72	4.00
SM175519-GS	24	4.655	111.72	4.00
SM185520-G	18	4.752	85.54	3.10
SM185520-GS	18	4.752	85.54	3.10

SM186017-G	18	4.460	80.29	2.92
SM186519-G	18	4.655	83.79	3.04
SM187517-G	18	4.460	80.29	2.92
SM195020-GS	18	4.752	85.54	3.10
SM195520-G	18	4.752	85.54	3.10
SM196519-G	18	4.655	83.79	3.04
SM196520-GS	18	4.752	85.54	3.10
SMT197020-GS	24	4.655	114.05	3.04
SM197518-G	18	4.558	82.04	2.98
SM197518-GS	18	4.558	82.04	2.98
SM198017-G	18	4.460	80.29	2.92
SM207016-G	24	4.363	104.72	3.76
SMT196521-GS	24	4.849	87.29	3.16
SMT195520-GS	24	4.363	85.54	3.76
SMT187019-GS	24	4.363	83.79	3.76

Table 14 Inventory control values for the safety lead time

In Table 15, we summarize the values per SKU for the reorder levels.

SKU	$SLT\ (hr)$	$s\ (GT)$
SM146020-G	4.07	52
SM147017-G	3.84	51
SM167016-G	3.76	50
SM168017-G	2.92	47
SM175019-G	4.00	51
SM175518-G	3.92	51
SM175519-G	4.00	51
SM175519-GS	4.00	51
SM185520-G	3.10	48
SM185520-GS	3.10	48
SM186017-G	2.92	47
SM186519-G	3.04	47
SM187517-G	2.92	47
SM195020-GS	3.10	48
SM195520-G	3.10	48
SM196519-G	3.04	47
SM196520-GS	3.10	48
SMT197020-GS	3.04	47
SM197518-G	2.98	47
SM197518-GS	2.98	47
SM198017-G	2.92	47
SM207016-G	3.76	50
SMT196521-GS	3.16	48
SMT195520-GS	3.76	50
SMT187019-GS	3.76	50

Table 15 Inventory control values for the reorder level

In Table 16, we summarize the values per SKU for the capacity validation. We find the safety lead time in green tyres by multiplying the safety lead time in hours with the demand per hour. The demand per hour is $\frac{34}{8} = 4.25\ green\ tyres$.

$\boldsymbol{SKU}$	$\boldsymbol{w}$ $(racks)$	$\boldsymbol{DR}$ (GT)	$\boldsymbol{SLT}$ (GT)
SM146020-G	1/24	714	17
SM147017-G	1/24	4284	16
SM167016-G	1/24	0	16
SM168017-G	1/18	51306	12
SM175019-G	1/24	714	17
SM175518-G	1/24	14688	17
SM175519-G	1/24	0	17
SM175519-GS	1/24	8976	17
SM185520-G	1/18	2142	13
SM185520-GS	1/18	510	13
SM186017-G	1/18	714	12
SM186519-G	1/18	0	13
SM187517-G	1/18	0	12
SM195020-GS	1/18	0	13
SM195520-G	1/18	0	13
SM196519-G	1/18	2142	13
SM196520-GS	1/18	131478	13
SMT197020-GS	1/24	63954	17
SM197518-G	1/18	100878	13
SM197518-GS	1/18	273360	13
SM198017-G	1/18	0	12
SM207016-G	1/24	0	16
SMT196521-GS	1/24	3060	13
SMT195520-GS	1/24	6630	13
SMT187019-GS	1/24	36414	13

Table 16 Inventory control values for the capacity validation

Appendix F: Relation safety factor z and CSL

To find the safety factor z with the desired cycle service level, we assume a normal distribution. Based on this, we look into the table from King (2011) in Figure 34 and to find the safety factor.

Desired cycle service level	Z-score
84	1
85	1.04
90	1.28
95	1.65
97	1.88
98	2.05
99	2.33
99.9	3.09

Figure 34 Relation of safety factor and CSL. Reprinted from King (2011)

Appendix G: NGT and product availability per month

To validate the increase in product availability, we take historical data to find out if the safety lead time indeed increases the product availability. Table 17 shows the NGT and product availability without the inclusion of the safety lead time. These correspond with the NGT values as stated in Section 1.5.1. Next, it shows the same values with the inclusion of safety lead time and the averages for both.

Month	Historical data		Historical data with SLT	
	NGT (%)	Product availability (%)	NGT (%)	Product availability (%)
November 2019	6.9	93.1	1.9	98.1
December 2019	1.8	98.2	0.5	99.5
January 2020	5.2	94.8	1.7	98.3
February 2020	3.8	96.2	1.0	99.0
Average	***4.4***	***95.6***	***1.3***	***98.7***

Table 17 NGT and Product availability per month

Appendix H: Supporting analytic

To support the KPI, we introduce the supporting analytic '*Number employees in the building and curing phase planned in succeeding shifts*'. The first two columns of Table 18 are already part of the daily report. Therefore, we expanded the table with two extra columns as shown in Table 18.

Shift	Net staffing future shifts	From which in building	From which in curing
A			
B			
C			
D			
E			

Table 18 Supporting analytic

Appendix I: Evaluation results

To validate that the chosen and visualized KPI is an effective tool to steer on product availability, we evaluated with the coordinators. We asked them the following questions, based on the three criteria to be effective. Question one is based on the importance of the KPI, question two on the ease of the KPI and question three on how actionable the KPI is.

1. How well does the KPI measure the quality of the inventory?
2. How well flows the quality of inventory directly from the KPI?
3. How well do we know by seeing the KPI how to improve the inventory?

We received the grades per coordinator per question shown in Table 19. We determined an average grade per question based on equal importance of the coordinators, which is also shown in Table 19.

	Coordinator 1	Coordinator 2	Coordinator 3	Coordinator 4	Coordinator 5	Average grade
Q1	7	8	10	10	8	8.6
Q2	8	8	10	10	9	9
Q3	9	7	10	10	8	8.8

Table 19 Grades per coordinator

Appendix J: Daily report with implemented KPI & supporting analytic

We implemented the KPI and the supporting analytic in the daily report of Space Master. This report is updated every shift and discussed once a day. Both the KPI and supporting analytic are used at the moment as shown in Figure 35. We circled the KPI and supporting analytic, respectively left and right, to indicate where the implementation can be found.

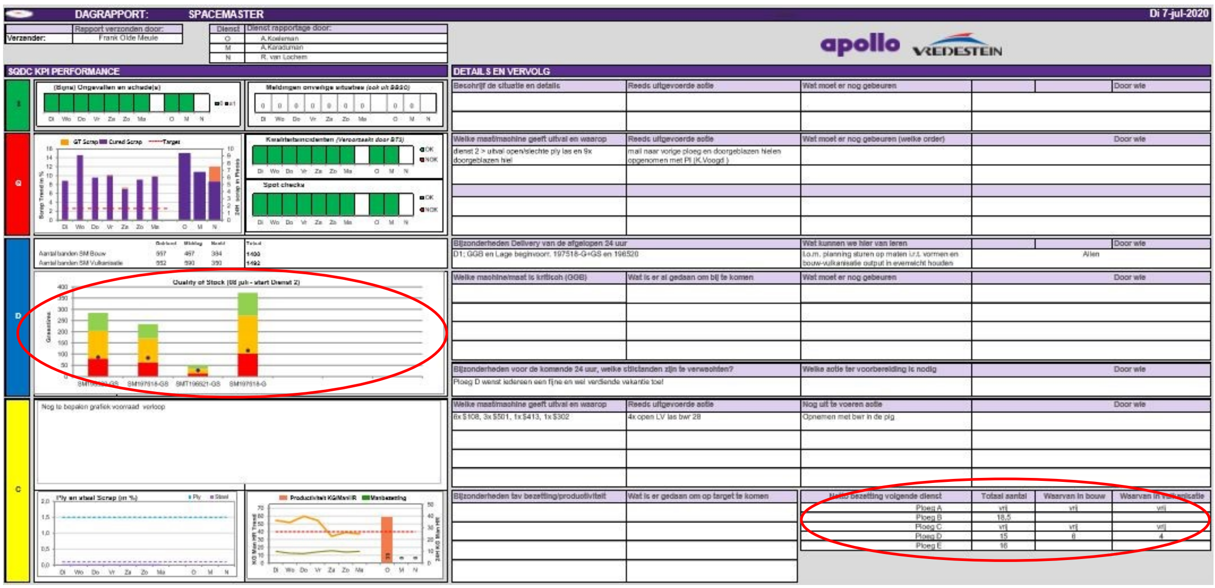

Figure 35 Daily report with circled KPI and supporting analytic