Increasing capacity utilization of the testing department of Apollo Vredestein B.V.

Master thesis

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[in this public version we removed some content because of confidentially matters]

MANAGEMENT SUMMARY

This master thesis provides recommendations to increase the capacity utilization at the Uniformity department of Apollo Vredestein B.V. This department is responsible for measuring the quality of the produced passenger car tires (PCTs) and is highly complex due to a dynamic Quality Control System and a varying flow of tires.

The motivation for this research arises from seasonal peak production periods, an increase in production volume, and the drive for increasing efficiency. When not using the capacity in a more efficient way, major investments are required. To meet the internal determined target for the year 2012, capacity utilization needs to be increased.

To increase capacity utilization, in this report we investigate the effective use of the measuring machines. This shows that the measuring machines are idle for about 30%. Due to setups and supply, the machines are idle for about 11% because of 1) inefficient machine design and 2) negative operator and truck driver influence. The remaining idle time is caused by machine failures, lunch breaks, operator unavailability, and changing shifts. Also, we identified the main disturbing factors influencing the capacity utilization. The following root causes of these factors have been identified: lack of well-defined Key Performance Indicators, lack of proper scheduling, high negative operator influence (due to limited amount of operators and lack of expertise), and inefficient machine design regarding setups and supply.

The challenge for the year 2012 is to increase capacity utilization for the uniformity machines by about 10% and for the X-ray machines by about 20%. To bridge this performance gap, we recommend implementing the following solutions:

- Reduce idle time during setups and supply by both technical and organizational measures
- Provide a dynamic scheduling component, taking care of uncertainty and complexity
- Develop well-defined Key Performance Indicators to provide insight into performance
- Reduce machine failures by providing a robust solution for the conveyor belt
- Temporarily increase the amount of workforce
- Provide training by introducing ‘best practices’ to increase operator expertise

This selection is based upon the criteria: improvement potential, costs, ease of acceptation, and implementation speed. If all of the solutions above are implemented successfully, the existing performance gap will be bridged.

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PREFACE

This Master thesis is the result of my graduation assignment of the study Technical Engineering and Management. During this study at the University of Twente, more and more I realized that this study was meant for me. Both the education at the University and the graduation assignment at Apollo Vredestein B.V. has been a learning experience and provide a valuable contribution for starting my career.

I thank Apollo Vredestein B.V. for giving me the opportunity to execute this assignment. Especially thanks to Edger Zuidema for his professional and motivating guidance. Second, I owe many thanks to my two tutors of the University, Waling Bandsma and Marco Schutten, for providing feedback on my approach and critically reviewing the content of this thesis.

Mom and dad, thanks for always supporting me during my study and making it possible to study anyway. Dad, thanks for the reflection-sessions in which I was confronted with the need for continuous improvement.

And of course I want to say thanks to my lovely wife for her support. You contributed to this thesis by always supporting me to spend time on study purposes and by your empathy during the progress of this thesis.

Pieter de Jongh
Hengelo, November 2011

CHAPTER 1 – RESEARCH APPROACH

In this chapter, we describe the research approach. Section 1.1 contains an introduction of the company and the department for which we execute this research. Next, Section 1.2 elaborates on the motivation for this study. Section 1.3 formulates the problem, which we transform into the research goal in Section 1.4. Section 1.5 provides a step-by-step plan, using a research model and research questions. In Section 1.6 we determine the research scope to provide a clear defined focus, whereas Section 1.7 describes the research design, elaborating on the research model.

1.1 INTRODUCTION

The company Apollo Vredestein B.V. is located in Enschede, The Netherlands and produces various types of rubber tires for passenger cars and agricultural vehicles. Different types of tires are produced at different departments in the factory. The production department that is responsible for the passenger car tires is called the department of 'Building & Vulcanisation'. Within this production department, a quality department called 'Uniformity department' is responsible for testing the quality of the produced passenger tires. This study focuses on this quality department that is responsible for measuring tire dimensions. Measuring the tires has two main functions: 1) to provide feedback to its prior processes and 2) to prevent that tires, not meeting the internal requirements, will be launched in the market. Whenever we use the word 'tires', we mean the tires for the passenger cars.

The required capacity for this department is influences by the Quality Control System. This system determines the testing requirements. Furthermore, the management of Apollo Vredestein is also anticipating an increase in yearly tire production. Also this influences the required capacity for this department.

In Section 1.2 we elaborate on the research motivation.

1.2 RESEARCH MOTIVATION

We split up the motivation for this research into two aspects: 1) high peaks in the current volume of tires to be measured by the Uniformity department and 2) the planned increase in tire production volume. This results in our observation, confirmed by Apollo Vredestein, that under certain circumstances, stagnation of tires at the Uniformity department occurs.

The Uniformity department faces high peaks in the number of tires supplied by the Vulcanisation department, which is prior to the process of the Uniformity department. Because the current capacity is not used enough, stagnation of goods within the Uniformity department occurs. However, as one can imagine, this is as an undesirable situation.

Besides this first aspect, the management has planned an increase in production volume. Production will grow from 5.3 up to 6 million tires this year, resulting in an even higher supply of tires at the Uniformity department. Both aspects lead to the undesirable situation, asking for the need of a thorough research to investigate the ways in which the use of capacity can be increased.

In the remainder of this thesis, we use the following definitions. “Capacity” is defined as the maximum output that can be obtained when continuously measuring tires, “capacity utilization” is defined as the use of capacity, and “required capacity utilization” is defined as the required use of capacity to handle the amount of incoming tires.

1.3 PROBLEM FORMULATION

The above leads to the following main question:
“In which way can the capacity utilization of the Uniformity department be increased?”

This problem formulation shows a close relation between capacity and throughput. Throughput can be increased in various ways, however the focus of this research is on increasing the capacity utilization.

When we use the term ‘problem’, we intend throughput- and capacity related issues. When the term ‘efficiency losses’ is used, we mean issues regarding non-value adding activities. These efficiency losses might, but do not always, harm the capacity utilization and throughput.

In order to answer the main question, several areas within the field of Operations Management have to be dealt with, including Lean Manufacturing and basic manufacturing principles. Using methods from these areas, we identify and map efficiency losses regarding performance and operations improvement, planning and scheduling, and internal logistics.

Section 1.5 discusses the research approach. First, we transform the problem formulation into the research goal.

1.4 RESEARCH GOAL

The goal of this study is:
to provide recommendations to increase the capacity utilization of the Uniformity department.

Section 1.5 describes the approach to reach the research goal.

1.5 RESEARCH QUESTIONS

Figure 1 shows the research model. The vertical arrows illustrate the confrontation (or interaction) aspect and the horizontal arrows illustrate conclusions that can be drawn from the confrontations.

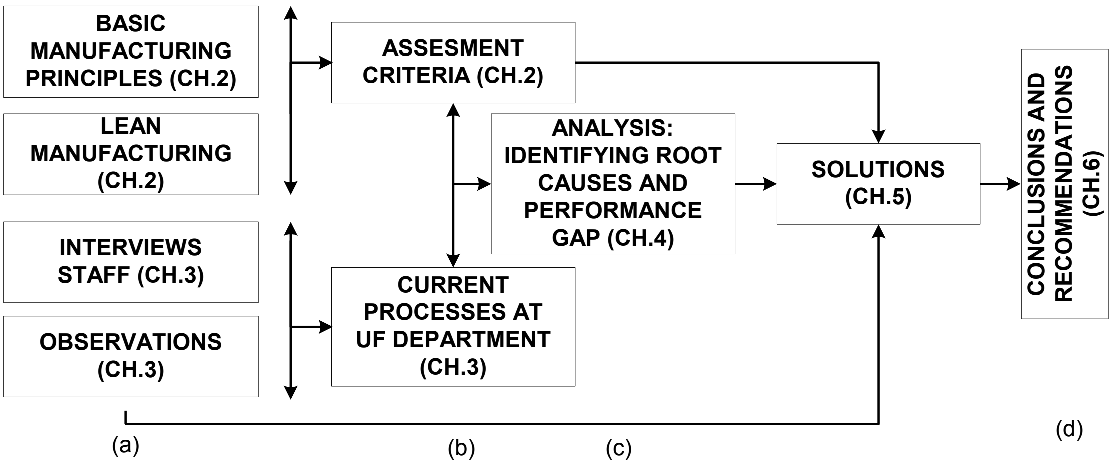

Figure 1: Research model including chapter indications (based upon Verschuren & Doorewaard (1995))

Whereas it might looks like that the process consists of mainly sequential steps, it is important to note that feedback is inevitable (see also Section 1.7).

To answer the main question and reach the formulated purpose, we formulate four sub questions.

Preparation: Literature study (Chapter 2)

Sub question I: *Which theories are relevant for analysing the output of a production department?*

i. Which theories are relevant for identifying efficiency losses in the current situation?

ii. Which assessment criteria can be set up, based upon the selected theories?

iii. Which theories are appropriate for identifying major problems and their corresponding root causes?

iv. Which theories will be useful for providing solutions?

Observation: Current process (Chapter 3)

Sub question II: *What are problems and efficiency losses in the current processes of the Uniformity department resulting in a realized output lower than desirable?*

i. How can the current main process at the Uniformity department, including external influences, be described?

ii. What impact do various influencing factors have on the realized output of the Uniformity department?

iii. How can the current situation be judged by the provided theories?

Analysis: Identifying causes of efficiency losses (Chapter 4)

Sub question III: *What are the underlying causes of the largest capacity related efficiency losses?*

i. How can the observed efficiency losses be ranked upon the assessment criteria, provided by the literature?

ii. What root causes can be identified for the largest efficiency losses?

Solutions: Solving problems & providing recommendations (Chapters 5 & 6)

Sub question IV: *What is an appropriate solution for the observed main problems?*

i. Which theories provide a good basis for proper solutions?

ii. On which criteria should the possible solution(s) be ranked upon?

iii. How can the impact of possible solutions be verified?

iv. Which solutions should be implemented to solve the capacity problem?

In Section 1.6 we present the research scope, providing direction.

1.6 RESEARCH SCOPE

This section provides direction for determining the research scope and the corresponding time aspects. We discuss these issues below.

We limit the research to the Uniformity department, i.e., from the incoming tires supplied by the Vulcanisation department to the point that the tires are delivered at the main warehouse for finished products. This can be visualized as follows (see Figure 2):

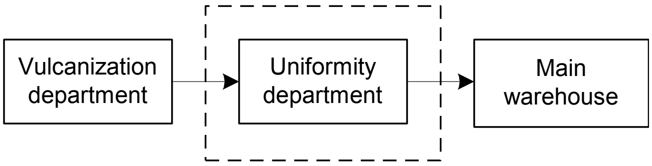

Figure 2: Illustration of the input and output of the Uniformity department

We exclude potential high-tech solutions, such as high-tech measurement improvements, from the scope. However, we take technical related solutions into account and include a quantitative aspect during this investigation.

As stated in the research purpose, the focus is on increasing the capacity utilization. When calculating the required capacity utilization, we use the available results of time studies (standard times). We compare this with the actual performance of the Uniformity department, using data from the Enterprise Resource Planning (ERP) system and by observing the situation.

The Uniformity department has several machines: two types of machines to perform the measurements (X-ray and uniformity measurement machines), a machine to label all tires, a trimming machine, and a nailing machine. We exclude the trimming machine and the nailing machine from the research due to their limited use.

Apollo Vredestein has internal regulations describing the testing method (a.k.a. Quality Control System). Since these regulations are out of scope, we exclude this from the research.

Also, the overall production plan influences the emergence of high peaks in the volume of tires to be measured. We exclude this from the investigation, i.e. the overall production plan, including peak production periods, is a given.

We limit the study to recommend on the currently formulated problem. The short term recommendations include improvements given the available resources, i.e., using the current resources in an efficient way. For long-term recommendations, investments may be required. Carrying out the implementation of any of these recommendations is not part of this research due to time constraints.

In Section 1.7 we elaborate on the research design.

1.7 RESEARCH DESIGN

To reach the formulated purpose of the research, we set up the following research design. Figure 1 (see Section 1.5) illustrates a research model to provide the necessary structure to walk through the process step-by-step.

The research model contains four main phases (a-d) to provide the following content: In phase a, we collect information from the available resources which we use as input for phase b. During phase b, we set up assessment criteria and we map current processes of the Uniformity department. During phase c, we analyse observed problems in order to identify root causes. During phase d, the final phase, we provide recommendations. This is the main goal of the research and all prior processes should contribute to this goal.

So far, it still seems like a sequential way of steps. However, the presence of feedback and feed forward is inevitable. Reflecting on achieved results provides direction for the research.

Next, we describe the research model in more detail to provide insight in the process.

(a) Available resources
The first step of this process includes a literature study on Operations Management (OM) regarding throughput related factors. This literature study is important since the main observed problem (see problem formulation) fits within the field of OM. We use the following literature, including: basic manufacturing principles (Hopp & Spearman, 2000) and concepts from Lean Manufacturing (including Value Stream Mapping (VSM)). We apply Lean Manufacturing because of its valuable tools and the familiarity of Apollo Vredestein with this concept. Based upon a first global analysis, we will define key problem areas. This provides direction to more specific theories in the field of OM to be applied during the analysis phase. The literature study shall provide valuable insights for mapping the current and future situation and for thinking in solutions.

Besides literature, we use the input of employees of Apollo Vredestein. Parties involved will provide valuable insights from their point of view. Various parties are included: managers, process engineers, industrial engineers, coordinators, and operators. Most parties are involved during every steps of the process.

Finally, we perform an observational study, interviews, and use data from the ERP-system. In the remainder of this thesis, with 'observations', we mean (the results from) an observational study, interviews, and/or available ERP-data.

(b) Current process and assessment criteria

The second step includes observing and mapping the current situation. We use a variety of theories to describe and analyse the current situation in terms of relevant theories (using basic manufacturing principles, Lean Manufacturing principles, and a planning framework). First, we investigate internal processes and external influences. After we mapped this global overview, we provide a selection of relevant observed problems (key problem areas) to be analysed in more detail. We assess this overview of key problem areas upon relevant criteria, set up by using the theory. During the next phase, we these areas into account for providing a more detailed analysis.

(c) Analysis: Identifying root causes and performance gap

The analysis of the current situation is the third step in this process. During this phase, we identify problems within the key problem area(s). Based upon an analysis regarding the impact of various factors on the main problem, we determine the underlying root cause(s) of the low capacity utilization. Also we illustrate the performance gap to determine what improvements are required to bridge the gap.

(d) Solutions and recommendations: Tackling problems & providing recommendations

The fourth and final step in this process starts with an idea generation process to construct potential solutions for the observed problems. Next, (if required) we collect additional theory to provide more specific insights in potential solutions. Here feedback plays an import role again. Also we organize a brainstorm session and perform various interviews as an additional source of input. After this phase, we provide solutions which we rank upon the prescribed criteria. Next, we write an implementation plan regarding the recommendations.

During the observation and analysis steps, we use data from the ERP-system as an additional resource. This system contains a variety of data including production volumes, actual throughput generated by each department (real time data), inventory levels, etc. Next to this data, a broad collection of standard times is available. This is based upon time studies performed by Apollo Vredestein. Based upon these times, various capacity calculations are made possible.

In this chapter we created an overview of the way the research will be executed. The motivation of this study arises from high peaks production periods, an increase in production volume, and the drive for increasing efficiency. During the peak production periods, stagnation of goods within the Uniformity department occurs. The main goal for this study is to provide recommendations to increase capacity utilization. The research questions describe how to solve the problem using literature, describing problems and efficiency losses, identifying root causes, and providing appropriate solutions and recommendations. Furthermore, we clarified that the research model consists of four phases to transform the various types of input into proper recommendations.

The remainder of this thesis is as follows. Chapter 2 describes relevant theories within the field of Operations Management (OM) that are used to identify, analyse, and solve the problem. In Chapter 3, we analyse the current situation, focusing on the identification of problems. Based upon assessment criteria, we select a key problem area for the main problem. In Chapter 4 we perform a detailed analysis regarding this key problem area. Based upon this analysis, Chapter 5 provides proper solutions for the main problem. Using several theories, methods, and the input from the involved people of Apollo Vredestein, we provide recommendations in Chapter 6.

CHAPTER 2 – THEORETICAL FRAMEWORK

In this chapter, we provide an overview of theories applied for identifying, analysing, and solving the capacity problem at the Uniformity department. As stated in the research design (see Section 1.7), first we perform a global analysis, followed by a more detailed and thorough analysis of a key problem area.

Section 2.1 gives an overview of the used theories and explains why these theories are valuable for this research. The next sections provide the fundamental essence of the theories: Section 2.2 provides the theories applied to describe and analyse the current situation and Section 2.3 mentions the importance of assessment criteria to be used to analyse the current situation upon and to provide a well-founded direction of a more detailed analysis. In Section 2.4 we describe how the root causes can be identified, after which Section 2.5 gives an overview of the way solutions will be provided using various sources.

2.1 OVERVIEW OF THEORIES

We apply the following theories and principles to identify, analyse, and solve the capacity problem at the Uniformity department: basic manufacturing principles, Lean Manufacturing, a Manufacturing Planning & Control framework (by Zijm, 2000), and the '5 why's method'. Below, we briefly describe why the theories are applicable for the problems observed at the Uniformity department.

The underlying reason why we apply Lean Manufacturing tools, arise from the following observed problems (which are confirmed by Apollo Vredestein):

- a high inventory level
- a lot of temporary storage
- a lack of space
- low machine availability and low capacity utilization
- high cycle and lead times
- and a lot of changeover activities

Zimmer (2000), Upadhye et al. (2010), and many others describe significant positive effects of Lean Manufacturing tools, including:

- Inventory reductions of more than 75%
- Floor space reduction of 80%
- Machine availability of 95%

- Cycle time reduction of 60%
- Changeover reduction of 80–90%

When we compare the observed problems with the reported effects of Lean Manufacturing, the application of this theory becomes almost inevitable. Using Lean Manufacturing tools, we will identify efficiency losses and potential areas of improvement, including the above stated problems.

Next to the above stated problems, additional problems are present (confirmed by Apollo Vredestein), including: a limited throughput (performing below par), variability and bottleneck issues, capacity restrictions, and a low capacity utilization. Basic manufacturing principles (Hopp & Spearman, 2000) distinguish from Lean Manufacturing by providing a more fundamental approach to manufacturing problem-solving. Therefore, at this stage these principles are applied in order to analyse the current situation. Also possible causes of common manufacturing performance problems are mentioned.

At Apollo Vredestein, the planning and scheduling activities seem to lack uniformity (see Section 2.2.3); every shift operates in a different manner. Since the planning and scheduling of activities significantly influence the performance and efficiency of a department (Schutten et al., 1996), we take this subject area into account during the analysis. A Manufacturing Planning & Control framework (Zijm, 2000) provides insight into planning areas that are relevant for this research.

Also we use the '5 why's method' to identify root cause(s) of the observed problems. Besides these useful tools, the applied theories already provide some foundation for identifying problems and solving its cause.

Section 2.2 describes the fundamental essence and the usefulness of above stated theories more extensively.

2.2 DESCRIBING AND ANALYZING THE CURRENT SITUATION

For describing and analysing the current situation, we apply a variety of theories, including: basic manufacturing principles (Hopp & Spearman, 2000), Lean Manufacturing principles (including the Value Stream Map tool), and a Manufacturing Planning & Control Framework (Zijm, 2000). Below, we describe the content of these theories.

2.2.1 Basic manufacturing principles

Basic manufacturing theories and principles are meant to structurally analyse and increase the performance of manufacturing organizations. The main focus to reach that goal is to improve processes to increase efficiency. This will increase performance such as capacity utilization, throughput, inventory, and quality (Hopp & Spearman, 2000).

Relevant topics for this research, based upon the observed problems, include: process variability, capacity, utilization, and throughput (limited by the bottleneck machine). Regarding these elements, we developed a model (see Figure 3) to map the interrelatedness of those elements. We applied dotted lines to illustrate that only the machine(s) with a limited throughput is defined as the bottleneck. The interrelatedness of each element can be visualized as follows:

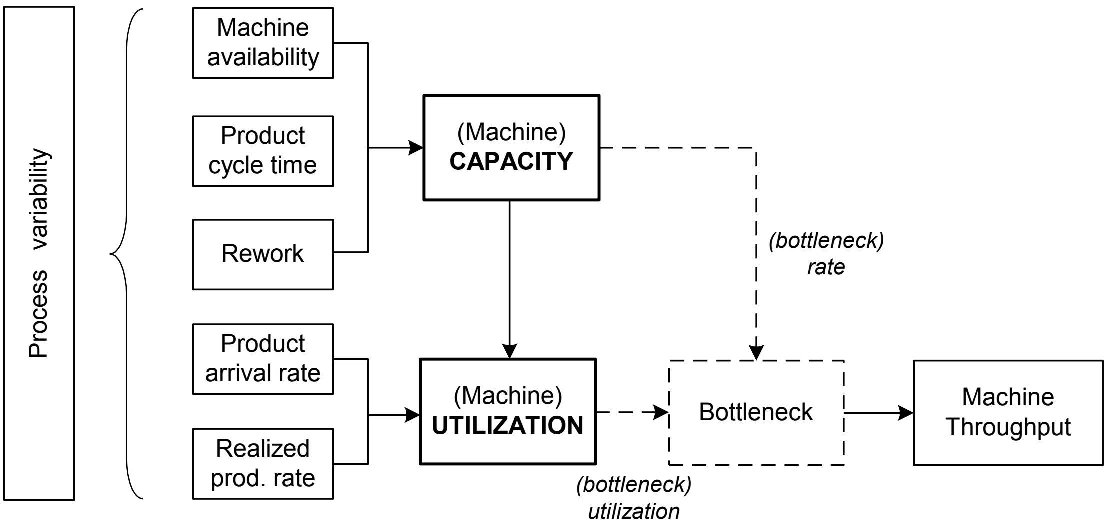

Figure 3: Overview of throughput related components

Next, we elaborate on the main elements of Figure 3.

Process variability

First of all, it is known that variability in processes decreases performance (Hopp & Spearman, 2000). The most common variability causes are (Hopp & Spearman, 2000):

- 'Natural' variability – fits within the category of preemptive outages[1]
- Random outages – fits within the category of preemptive outages
- Setups – fits within the category of *non*preemptive outages[2]
- Operator unavailability – fits within the category of *non*preemptive outages
- Recycle – rework

[1] Preemptive outages are disturbances that can occur at every sudden moment e.g. they can occur right in the middle of a job (Hopp & Spearman, 2000)

[2] *Non*preemptive outages are stoppages that occur between, rather than during, jobs (Hopp & Spearman, 2000)

Capacity

Capacity is defined as: "*an upper limit on the throughput of a production process*" (Hopp & Spearman, 2000, p.216). This implies that, to be stable, each workstation must have a processing rate that is *strictly greater* than the arrival rate at that station. If not, WIP levels continue to grow and never stabilize (Hopp & Spearman, 2000).

Utilization

Utilization is defined as: "*the fraction of time the station is not idle for a lack of parts*" (Hopp & Spearman, 2000, p.218). This includes the time that the machine is working on a product, or needs to wait on processing the product due to a machine failure, setup, and all other detractors.

Bottleneck

The bottleneck is defined as: "*the process or … workstation having the highest long-term utilization*" (Hopp & Spearman, 2000, p.218). Long-term implicates that outages due to machine failures, operator breaks, quality problems, etc. are averaged out over the time horizon. As Hopp & Spearman (2000) conclude: increasing capacity of a bottleneck station will have a larger impact on the throughput than increasing capacity of other workstations. Therefore, it is important to identify the bottleneck at the Uniformity department.

Throughput

Throughput is defined as: "*the average output of a production process per unit time*" (Hopp & Spearman, 2000, p.216). The throughput (TH) is influenced by the bottleneck in the following way: TH = bottleneck utilization x bottleneck rate (Hopp & Spearman, 2000). This implies that the throughput can be increased in two different ways: 1) by increasing the bottleneck rate or 2) by increasing the bottleneck utilization.

Besides this, four efficiency measurements (Hopp & Spearmen, 2000) are applied to measure current performance:

- Throughput efficiency (E_{TH}): whether output is adequate to satisfy demand, so that $E_{TH} = \frac{\min\{TH, D\}}{D}$ where TH = average throughput (parts/day) and D = average demand (parts/day). The upper term is the minimum of the throughput and demand to ensure that the throughput efficiency can not exceed 1.
- Utilization efficiency (E_U): the fraction of time station i is busy, so that $E_U(i) = \frac{TH(i)}{r^*(i)}$ where TH(i) = average throughput of station i (parts/day), and r^* = maximum obtainable production rate of station i (parts/day)

- Cycle time efficiency (E_{CT}): ratio of raw processing time and average cycle time, so that $E_{CT} = \frac{T_0^*}{CT}$ where T_0^* = raw processing time, defined as processing time not including detractors (sec.) (Hopp & Spearman, 2000, p.292) and CT = average cycle time (sec.). Since CT is always larger than T_0^*, $E_{CT} < 1$.
- Lead time efficiency (E_{LT}): the ratio of raw processing time and average lead time, so that $E_{LT} = \frac{T_0^*}{\max\{LT, T_0^*\}}$ where T_0^* = raw processing time, defined as processing time not including detractors (sec.) and LT = average lead time quoted to customer (sec.).

Appendix A provides a variety of 'manufacturing laws' illustrating generic statements regarding the above factors. An overview of the main effects of variability on the performance of production lines is depicted in Appendix B.

Usefulness of basic manufacturing principles

Using basic manufacturing principles, we measure the performance using efficiency measurements and we apply manufacturing principles to judge the current performance. Based upon the capacity utilization and a bottleneck analysis, we determine the feasible throughput and we analyse the impact of the variability on the overall performance. This provides a good basis for the assessment of the current situation, based upon fundamental manufacturing theories and principles.

Section 2.2.2 elaborates on the use of Lean Manufacturing.

2.2.2 Lean Manufacturing principles

To understand the essence of Lean Manufacturing, a very brief description is given first:

"*The only thing we attempt to do in lean-production is letting each process produce what its consecutive process needs, at the moment that it is needed. We try to connect all processes – from the end user (back) till the raw materials – in a smooth flow without detours, resulting in a lead time as short as possible, with the highest quality against the lowest costs.*" (Rother & Shook, 2003, p.43)

Lean Manufacturing is a philosophy with the aim of eliminating waste ("muda")[3] (Womack & Jones, 2007). Waste can be best described as non-value-adding activities for which the customer does not want to pay for. A variety of waste-categories are set up by Ohno (1988)

[3] The term "muda" is Japanese for "waste" and is often used instead of the English term.

and described by Womack & Jones (2007). The different types of waste can be categorized into 7 categories: 1) Transport, 2) Inventory, 3) Movements, 4) Waiting, 5) Overproduction, 6) Over Processing, and 7) Defects. The Uniformity department will be analysed based upon these 7 categories of waste.

The Lean Manufacturing philosophy includes various tools to eliminate waste. From these tools, we apply the Value Stream Map (VSM) and the 'spaghetti diagram'. A Value Stream Map (VSM) is a Lean tool to map the flow of materials and information to identify efficiency losses. The Value Stream Map includes value adding and non-value adding activities required to bring a product from raw materials to the customer. A VSM is applied since this is a common tool for Apollo Vredestein. We apply this to provide an initial overview of all processes. Besides this, we map a 'spaghetti diagram' containing non-value-adding operator and truck driver movements. Based upon these results, we execute a more detailed analysis. The aim of eliminating non-value adding activities is taken into account during the entire research.

Since in Lean Manufacturing (non)value-adding activities play a central role, we define the (non)value-added activities at the Uniformity department. Value-added-time does depend on the definition of value, which in fact can only be defined by the end customer. The end customer decides what to pay for and what not to pay for (Womack & Jones, 2007). This implies that the measuring activities do not add any value from most customers' point of view. However, at Apollo Vredestein, the Uniformity department contributes to guarantee the high quality of the produced tires. This high quality is an internal requirement from the warehouse (and the whole organization): they only accept (tested) high quality tires. From this internal point of view, the activity of measuring the tires can be seen as value-added-time. Also labeling the tires can be categorized as value-added-time, since it is both an internal and external requirement.

In Appendix C we provide more details of the main elements of the Lean Manufacturing philosophy. The following elements are included: the 7 categories of waste, the 5 Lean principles, and Value Stream Mapping (VSM).

Usefulness of Lean Manufacturing for this research

The Lean Manufacturing theory provides a valuable contribution for this research since many observed problems are strongly related to efficiency losses (see Section 2.1). These problems and efficiency losses are observed and confirmed by Apollo Vredestein. The VSM technique is applied to map the current state of processes. This provides valuable insights in efficiency losses of the processes, starting at the supply of tires from the vulcanisation department up to delivery to the main warehouse. Based upon this analysis, a global process overview is mapped and improvement areas are being created. This will provide a good basis for a more detailed analysis in a specific direction.

In Section 2.2.3 we describe the usefulness of the Manufacturing Planning & Control framework.

2.2.3 Manufacturing Planning & Control Framework

We use the Manufacturing Planning & Control (MPC) framework (Zijm, 2000), see Figure 4, to classify relevant planning activities after which we discuss its impact on operational performance. This is relevant since the planning and scheduling activities have a significant impact on operational performance. The framework is general in the sense that it includes Make-To-Stock, Make-To-Order, and many more systems (Zijm, 2000). Therefore this framework can be applied to the current case. When the term 'planning framework' is used in the remainder of this report, the Manufacturing Planning & Control Framework is meant.

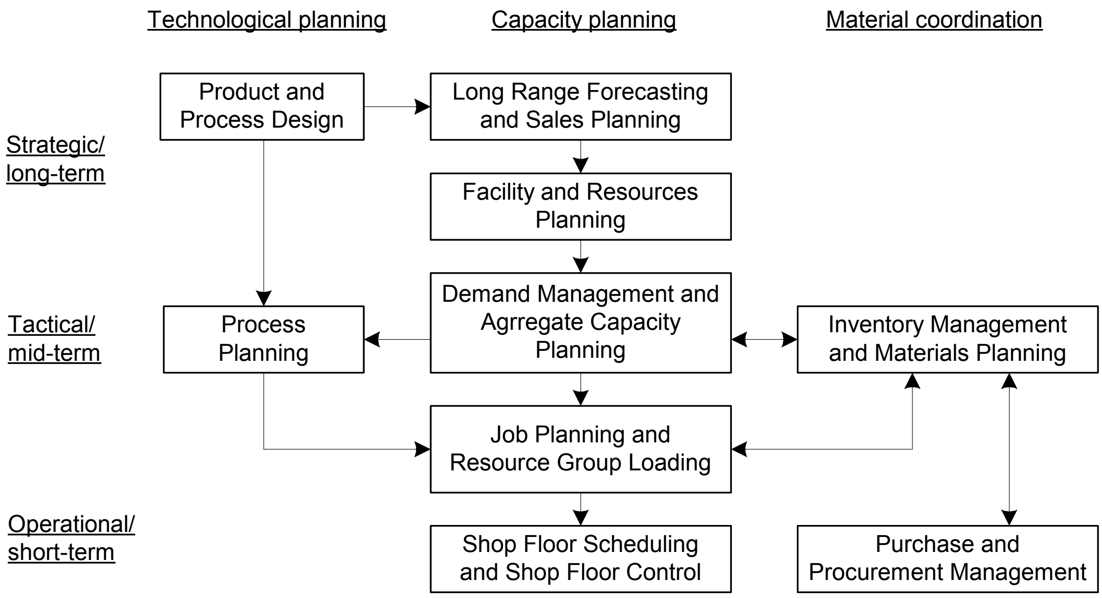

Figure 4: A manufacturing planning and control reference architecture Source: Zijm (2007)

Usefulness of the MPC framework for this research

The planning framework consists of three hierarchical levels of control (strategic, tactical, and operational) and three functional planning areas (technological planning, resource capacity planning, and material coordination). Using this grid, we classify planning activities after which we select planning methods from within this classification area to improve current planning activities. This framework clarifies that planning decisions at operational level are influenced (and restricted) by planning decisions made at strategic level.

Planning and scheduling at the Uniformity department have to take into account: precedence relations, changeover times, restricted capacity, uncertainty and variability. This makes the planning and scheduling process complex. According to Zijm (2000) and Hans et al. (2007), complexity and uncertainty are major factors influencing the ease of planning activities. This subsequently influences the performance and throughput of an organization or department and makes the planning framework relevant to include. In Section 3.3 we apply this framework. Next to these theories, assessment criteria are set up to judge the current situation upon.

2.3 LITERATURE PROVIDING CRITERIA TO ASSESS THE CURRENT SITUATION

This section describes how we assess the current situation and how we determine a legitimate focus for a detailed analysis.

Using observations and interviews, we describe the relevant processes of current situation. Also we analyse data to provide more insight into the current processes and performance. The literature, as described in the previous sections, provides the main criteria to assess the current situation upon. Using a VSM, various efficiency measurements, and the planning framework, we perform a global analysis. We execute this assessment in Chapter 3. Based upon this analysis, we execute a more detailed analysis in Chapter 4. After we finish the analysis phase, we set up criteria to rank potential solutions upon in Chapter 5.

Section 2.4 discusses how to identify the root causes.

2.4 IDENTIFYING CAUSES OF OBSERVED PROBLEMS

After we have identified various problems in Chapter 3, we select the main problems harming the throughput most. This is done by applying the literature (containing assessment criteria), as described in Section 2.3. The next step is to identify root causes of the main problems. We use the '5 why's method' (Liker, 2004) to explore the cause-effect relationship underlying the observed problem(s). The 'why-question' needs to be repeated until the root cause is identified. Although the name implies asking why a total of five times, some situations require fewer or more than five questions (Chen et al., 2010). The result of the '5 why's method' can be visualized using a fishbone-diagram (Ishikawa, 1990) or a table-structure. The fishbone-diagram allows focusing on specific cause categories whereas a table-structure provides a good overview of all causal links.

This method is used during the analysis phase of the research and provides an answer on the question which main causes are responsible for the observed problems. The '5 why's method' can be shown as a process flowchart containing five sequential steps, see Appendix D.

2.5 PROVIDING SOLUTIONS

After we have analysed the current situation, we present an overview of relevant elements after which we discuss the interrelatedness between those elements. Next, we provide proper solutions, based upon a variety of sources. First of all, the applied theories provide direction in potential solutions. This is completed with additional theories concerning the potential direction of solutions. Also, we organize a brainstorm session to discuss the results of the analysis, resulting in potential solutions.

In Chapter 3 and 4 we apply the following theories to describe and analyse the current situation: basic manufacturing principles, Lean Manufacturing, a planning framework, and the '5-why's method'. In Chapter 5 we provide solutions, based upon the literature and the organized brainstorm session. Next, in Chapter 3, we describe and analyse the current situation to identify the current problems and efficiency losses.

CHAPTER 3 – CURRENT SITUATION

This chapter describes the current situation at the Uniformity department, including the observed problems. Based upon the assessment criteria, provided by the literature (see Section 2.3), we provide a global analysis. First, Section 3.1 describes internal processes and external factors influencing these processes. Next, in Section 3.2, we identify problems regarding process efficiency losses; a Value Stream Map is created to illustrate the various types of waste, whereas the planning framework is applied to categorize the planning activities. Using various basic manufacturing principles, we identify and analyse the factors influencing the capacity utilization and throughput in a global way. Section 3.3 illustrates efficiency losses regarding planning activities and its influence on the current performance. Finally, Section 3.4 determines direction for a more detailed analysis.

3.1 PROCESSES AND FLOW OF TIRES

As indicated before (see Section 1.1), the Uniformity department is responsible for testing the tires on specific prescribed criteria. The goal of testing the tires is: 1) to ensure the quality of tires to be sold in the market and 2) to provide quality feedback to the production departments. To perform activities corresponding to this goal, the Uniformity department consists of several internal processes, which we describe first. See Figure 5 for a global overview of the processes. External factors influencing these processes are discussed next.

[this figure is left out because of confidentially matters]

Figure 5: global overview of process steps at the Uniformity department

This process consists of six major steps:

1. Tires are delivered from the Vulcanisation department
2. Tires are stored in the ‘temporary’ storage area
3. Tires are picked and are transported to the measurement machines
4. Tires are measured
5. Tires are transported to the labelling machine
6. Tires are labelled and transported to the main warehouse

First, the incoming tires, supplied by the Vulcanisation department, are stored. Next, according to schedule, tires are picked to be measured. After the tires have been measured, they are labelled after which the tires are transported to the main warehouse for final storage.

Figure 6 provides the flow of the tires from the arrival at the measurement machine until the departure towards the labelling machine. This flow is relevant when discussing this process more in detail. It should be mentioned that a single truck driver is assigned to supply and remove the pallets at every single machine. We provide a detailed analysis in Section 4.1.

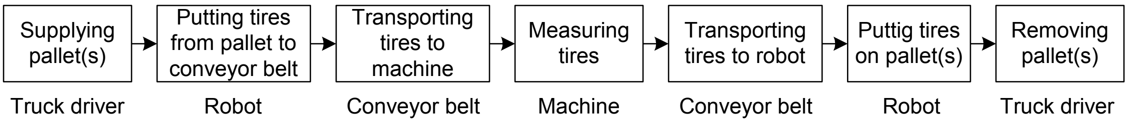

Figure 6: flow of tires from arrival until departure

The tires are transported on pallets to supply the robot. The robot picks the tires from the pallet and puts the tires on the conveyor belt. The conveyor belt transports the tires to the machine where the measurement is performed. Next, the tires are transported back to the robot, using a conveyor belt. The robot picks the tires from the conveyor belt and puts the tires back on the pallet. Finally, the truck driver transports the pallet.

3.1.1 Main processes at the Uniformity department

In this section, we describe the main processes to create a better understanding of the way the Uniformity department currently operates. *[here, some confidential content is left out]*

The main processes at the Uniformity department consist of logistic and measuring activities. Detailed flowcharts of the operational activities regarding the logistic and measuring activities can be found in Appendix F. In Section 3.1.2, the external factors influencing the internal processes, are discussed.

3.1.2 External factors influencing processes at the Uniformity department

Next to the description of the main processes, it is important to notice the impact of external factors on the main processes. The Uniformity department cannot influence these factors.

Overall production planning

The first external factor influencing the processes at the Uniformity department is the overall production planning. Based upon expected customer demand, determined by the marketing department, a long-term production plan is set up. This is converted into a weekly plan and results in a diversity of tires (differing in diameter size) to be measured. As one can imagine, this influences the required capacity at the Uniformity department. The Uniformity department has no right to decide upon this overall production planning and has to deal with the diversity of incoming tires.

Quality Control System

The Uniformity department measures its tires according to the Quality Control System. The way this system is set up, influences the processes of the Uniformity department.

3.1.3 Peak production periods

The motivation for this research mainly lies in the peak production periods in which stagnation of tires occurs. To get more insight into the volume of the tire to be measured, we provide the following overview (see Figure 7).

[this figure is left out because of confidentially matters]

Figure 7: production during the year (based upon ERP-data Apollo Vredestein)

This overview shows that the peak production periods occur in the months March, April, and May. To determine the tire type(s) responsible for the main flow during peak production periods, we set up a tree structure (see Figure 8). This shows that the tires with speed index Y contribute for 62% of the total number of measurements during peak production periods. Therefore the initial focus will be on this tire type (called 'Y-tire' in the remaining part of this thesis). Appendix J provides an overview of the calculations of the main flow during peak production periods.

[this figure is left out because of confidentially matters]

Figure 8: number of measurements per type of tire during peak periods (based upon ERP-data Apollo Vredestein)

The calculations are based on the number of measurements for the Uniformity department of 2010. Using the Y-tire we are able to map a representative overview of main processes at the Uniformity department. Section 3.3 elaborates more on the Value Stream Map of the Y-tires.

Section 3.2 elaborates on observed process related efficiency losses.

3.2 PROCESS EFFICIENCY

As explained in Chapter 2, a Value Stream Map is a Lean Manufacturing tool to map the flow of materials and information to identify efficiency losses. In this section, we apply this tool on the current situation. Next to that, efficiency measurements are applied. In Section 3.2.1 we start describing the process using performance indicators after which we set up the VSM in Section 3.2.2, illustrating efficiency losses in the current situation.

3.2.1 Efficiency measurements

This section provides various efficiency measurements, illustrating the current performance. First, we identify the bottleneck to emphasize the main process limiting the current output.

The bottleneck

The bottleneck is defined as the process or activity having the highest utilization (Hopp & Spearman, 2000). The higher the utilization, the higher the need for that process or activity to be running smooth continuously (processing the maximum number of parts). At the Uniformity department, both uniformity machines (5 and 6) and both X-ray machines (1 and 2) have a high arrival rate compared to their effective production rate (see Figure 9).

It should be noted that the capacity of both uniformity machines is in many cases exchangeable; a lot of tires can be measured by either uniformity machine 5 or machine 6. This also holds for both X-ray machines. Therefore a joint utilization is representative.

Figure 9 represents the utilization based upon 1) the maximum production rate and 2) the effective production rate. This provides more insight into the current performance.

The required utilization is 81% for the uniformity machines and 85% for the X-ray machines. Since the uniformity (5 and 6) and X-ray (1 and 2) machines require the highest utilization, these machines can be defined as the bottleneck of the Uniformity department.

Uniformity machine 1 has a limited arrival rate due to machine restrictions; this machine can only measure tires with a limited diameter size. The labelling activity has capacity flexibility since labelling the tires can be done by hand. Even when this machine is idle for a substantial amount of time, the tires get labelled. Therefore, these machines can be categorized as non-bottleneck resources.

[this figure is left out because of confidentially matters]

Figure 9: Machine utilization (based upon internal data of Apollo Vredestein)

Below we provide four efficiency measurements, as provided by Hopp & Spearman (2000), to show the current performance during peak production periods.

Throughput efficiency

[here we removed some content, because of confidentially matters]

Based upon data from the ERP-system of Apollo Vredestein the throughput efficiency is calculated, illustrating that efficiency improvement is present. See Appendix K for full calculations.

Utilization efficiency

This efficiency indicator is defined as the effective use of capacity and is calculated using the average throughput and maximum production rate. The maximum production rate is defined as maximum production rate observed in practice. Since this is realized in practice, we believe that this is a realistic norm to judge the average throughput upon. This leads to a utilization efficiency for the X-ray machines of (1050 / 1601 =) 66%. We executed the same calculation for the uniformity machines; see Figure 10 for the result. The result illustrates that only a relative small percentage (66 - 68%) of the capacity is used in practice. See Appendix K for the full calculations.

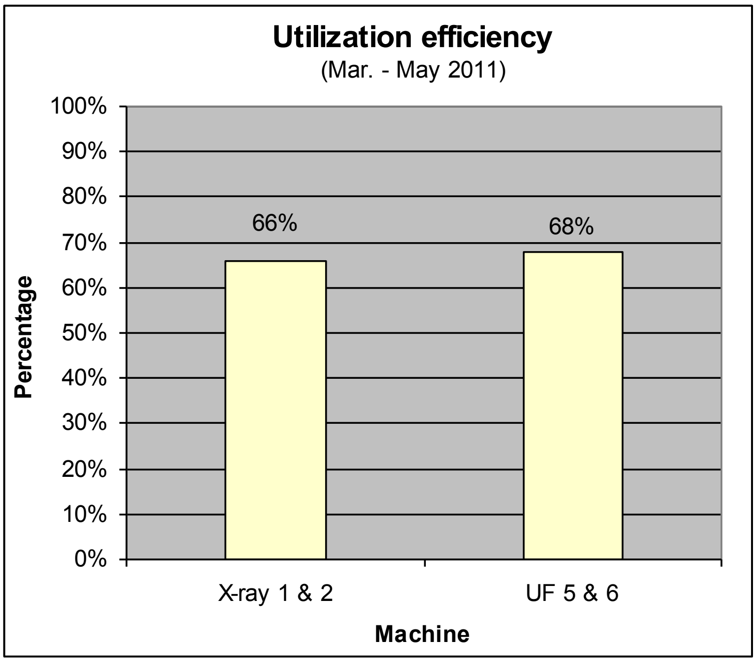

Figure 10: Overview of utilization efficiency (based upon ERP-system data)

Cycle time efficiency

The cycle time efficiency is defined as the proportion of time a tire is measured on a machine compared to its total (cycle) time on that machine. Because this is machine related, the cycle time efficiency rate is calculated for both uniformity and X-ray machines (see Table 1). This is calculated by dividing the processing time (i.e. duration of the measurement) by the total time a tire spends on the machine.

Machine	Cycle time efficiency	
UF 5	(20 / 114 =)	17.5%
UF 6	(17 / 117 =)	14.5%
X-ray 1	(34 / 125 =)	27.2%
X-ray 2	(24 / 178 =)	13.5%

Table 1: cycle time efficiency

These values illustrate that only a small percentage of the total cycle time is actually used measure the tire. The remaining time is contributed to material handling. The difference between both X-ray machines can be explained by the fact that the measurement of X-ray machine 1 is slower than machine 2 while the total time a tire spends on this machine is less than machine 2.

Lead time efficiency

Based upon the value-added[4] time and the total lead time, the lead time efficiency rate is calculated. This gives an indication of the part of the time a product spends on a certain department compared to the value that is added during that time. The total lead time is defined as total time a tire spends on the Uniformity department, i.e. from the incoming tires supplied by the Vulcanisation department until the point that the tires are delivered at the main warehouse for finished products.

World-class organizations, 'living the Lean philosophy', perform close to 30%. For the Uniformity department, the average lead time (of the main flow) equals 5.04 days whereas the value-added time lies between 42 and 59 seconds (see Figure 11). This results in a lead time efficiency of 0.014%. Whereas this comparison might not be quite fair due to differences regarding strategy, philosophy, and product, it does indicate that lead time efficiency improvement potential is present.

Conclusions

Based upon the above performance indicators, we conclude that: 1) the current throughput utilization is low, 2) the capacity utilization is low, 3) the cycle time efficiency (machine concerned) is low because of material handling activities, and 4) the lead time efficiency is too low since the agreed lead time may not exceed 3 days.

The above performance indicators show that the current efficiency at the Uniformity department is relative low and that areas with potential for improvement are present.

3.2.2 Identifying waste

The initial step of the VSM is mapping the current state. This includes selecting a product family. This product family should represent the main processes to be analysed. As already discussed, the Y-tire represents 62% of the total measurements during peak production periods. It is considered representative for the main flow of goods during peak production periods. This tire type will be used to map the current process, from the incoming goods until

[4] Both the measurements and labelling of tires are defined as value-added activities (see Section 2.2.2)

the transport to the main warehouse. For this product family, we map the material and information flow.

Figure 11 shows the result of the VSM including observed efficiency losses based upon the 7 types of waste. We elaborate on these efficiency losses, making it clear which types of waste contribute for a major part to the low efficiency rates. These are areas with potential for improvement.

Value Stream Map of Y tire

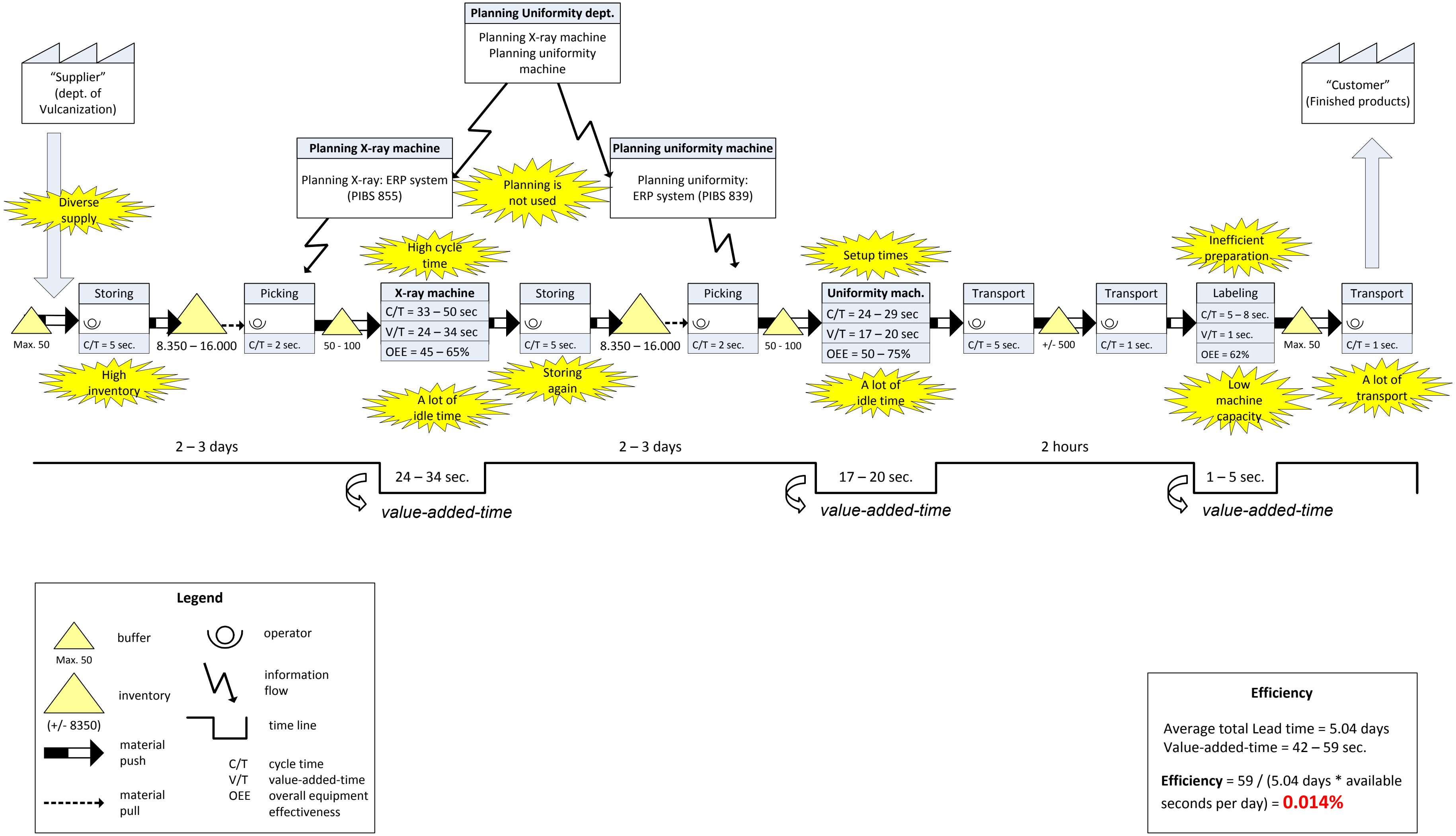

Figure 11: Value Stream Map of Y-tire

Transport

We observed that processes at the Uniformity department consist of many non-value-adding but necessary transport activities, see Figure 12. The main transport consists of trucks driving up and down, transporting the tires. This process starts at the incoming goods section where the tires are transported to the temporary storage area (TSA). Next they are transported to one of the measuring machines after which they are transported back to the TSA. Afterwards, they are transported again from the TSA to one of the measurement machines. After this process, the tires are transported to the labelling area after which they are labelled and transported to the main warehouse for their final storage.

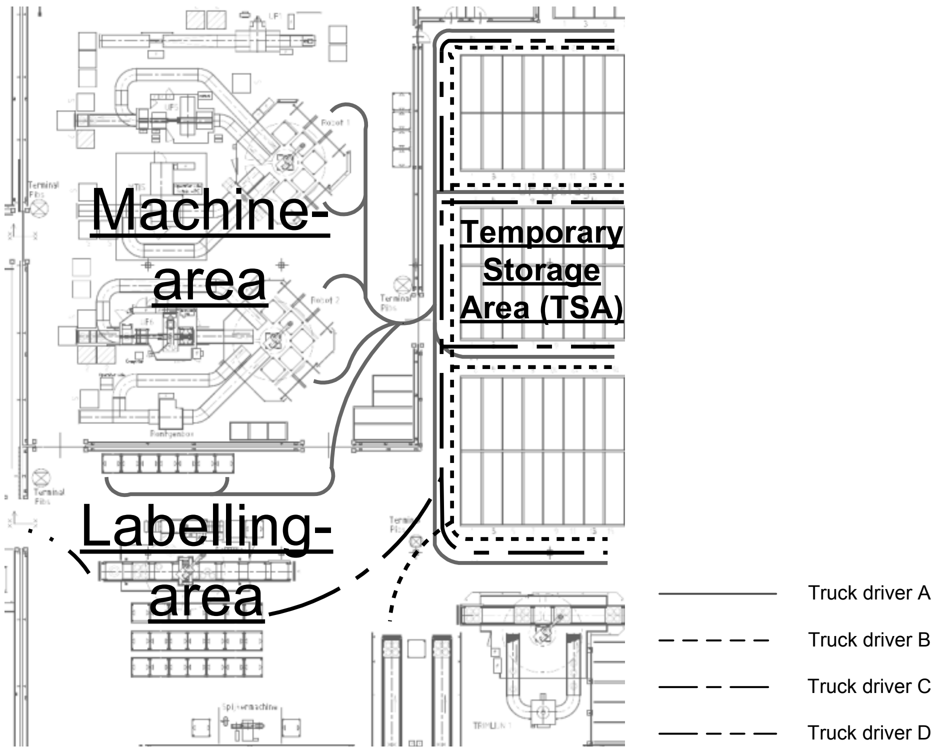

Figure 12: non-value adding transport activities (each pattern represents a truck driver)

Inventory

The inventory, which is in fact a temporary storage area (TSA), is used as a buffer. Especially during peak production periods, inventory levels are very high, causing long lead times (until the tires reach the final warehouse) and transportation and storage costs. This is apparent from the inventory level of the Y-tires (+/- 12.000) and the demand for these tires per day (+/- 3.000). This means that the tires are stored for about 4 days before they are measured. The inventory of the Y-tires equals up to 16.000 tires during peak production periods. This is unacceptably high and perceived as undesirable by Apollo Vredestein since the lead time is exceeded and an unmanageable situation occurs. Besides this, the more time between production and testing of the tires, the less useful the quality feedback. The high inventory does not add any value for the customer and can be eliminated.

In general, high inventories hide a lot of Operations Management related problems such as: production imbalances, defects, equipment downtime, and long setup times. This leads to sub optimal behaviour, such as reducing the motivation to continuously improve operations (Liker, 2004). We observe several of these issues at Apollo Vredestein; production imbalances (high variety in amount of measured tires: 1300 - 2100), downtimes (occurs frequently: every single day machine failure is reported), and long setup times (frequently 7 minutes for every single setup).

Movements

Analysing the movements shows that that many non-value-adding movements are performed, including operators walking from and to the machines, truckers driving up and down empty loaded, and the transportation of tires on the conveyor belt of the machines. Most movements are unnecessary and can thus be eliminated. For example, a better preparation of tasks by both the operators and truckers will decrease the number of movements. It should be mentioned that the movements of tires on the conveyor belt cannot be eliminated easily since it provides a valuable buffer for the machine. In Appendix L we show a layout diagram including the unnecessarily operator movements.

Waiting

We observe several waiting efficiency losses mainly related to 1) waiting of tires to be processed and 2) idle time (or downtime) of the machines. Most of the time a tire spends on the Uniformity department is in the temporary storage area (4 days, as discussed above). Next to that, tires are often stored temporarily as a buffer for the machine on which the tires need to be measured. Also, the tires are stored often temporarily just before they are labelled. Next to that, tires are transported on the machine using a conveyor belt. During this transportation, we observed that this frequently leads to waiting time for the machine.

However, the main and most relevant one, we observed using an observational study and data from the ERP-system, is the time a machine is idle (or down). This immediately affects the capacity utilization of the machines, and thus the throughput. We observe that waiting time of the machines occurs too much (see VSM and utilization efficiency) and costs a valuable amount of time (about 7 hours every 24 hours). This corresponds to the calculated utilization efficiency since capacity utilization is close to (1-7/24 =) 71% which corresponds with 66 - 68% as calculated in Section 3.2.1. This idle (or down) time can be clearly categorized as an unnecessary activity. This should be eliminated since it consumes a valuable amount of bottleneck resource. This harms the capacity utilization and (thus) throughput. Idle (and down) time of the machines is investigated further in the remaining part of this research.

Overproduction

This type of waste can better be called ‘over-measuring’ which means measuring more tires (to guarantee a certain quality) than demanded by the final customer. However, since the measuring regulations (Quality Control System) are out of scope for this analysis, we do not take this type of waste into account in the remaining part of this thesis.

Over-processing

Over-processing is defined as efficiency losses due to complex solutions for simple problems. The most obvious over-processing activities include the X-ray measurement and the way labelling-preparation activities are designed. The X-ray measurement is done by a machine, after which the result of the X-ray scan is visually inspected. This visual inspection, performed by an operator, limits the speed of the X-ray measurement to the human’s capability. This can be categorized as necessary waste since the current system makes it necessary that an operator inspects the tires visually. This cannot be done in another way immediately. Besides this, as indicated in the VSM, the preparation-labelling activities are done in a cumbersome manner: the labels are stored close to the labelling machine but are moved to an office at the other side of the department where the labels are printed. Next, the printed labels are moved back towards the labelling machine. Because of this ‘design’ it requires more process steps, and thus more work than needed. This is clearly a waste which can be eliminated easily.

Defects

Defects are defined as incorrect measurements due to an incorrect way of measuring. This implicates that whenever tires needs to be re-tested, this can be defined as waste from the perspective of measuring tires right the first time. Rework should be reduced; measuring right the first time. It turns out that most tires are measured correctly the first time, but that a percentage of 5% is re-tested. This type of waste can be categorized as an unnecessary type of waste since it can be eliminated within a reasonable amount of time.

Based upon the VSM analysis, we identified a variety of efficiency losses which we take into account when determining the direction for a more detailed analysis.

3.2.3 Conclusion

From the information obtained from the above observations and analyses we draw the following conclusions:

- Both measuring machines (X-ray and uniformity) have been identified as the bottleneck based upon their utilization.
- The utilization efficiency turns out to be relative low, directly influencing the capacity utilization.

- Defects (resulting in re-tests) have a direct impact on the required capacity utilization and will be taken into account.
- The lead time efficiency shows that the lead time is relative long and results in not meeting the agreed lead time and, more important, long lead times result in delayed quality feedback to production.
- Waste regarding over-processing has been observed regarding the X-ray measurements and the labelling-preparation activities. This is taken into account when providing recommendations.
- A major efficiency loss concerns the amount of idle (and down) time of both bottleneck machines. This directly influences the capacity utilization and (thus) the throughput. This is further investigated in the remaining part of this thesis.

As shown above, waste has an adverse effect on the capacity utilization of the machines and thus on the performance of this department. These activities need to operate as smoothly as possible and will therefore be taken into account during the analysis phase.

The main efficiency losses, limiting the current performance, are:

▪ Machines perform below par	indicated by the utilization figures
▪ A lot of waiting time	idle (and down) time of both measuring machines
▪ Complex feeding[5] of machines	indicated by the flow of transportation activities
▪ Various retests	Various tires are measured twice
▪ Long lead time	agreed lead time is frequently not met

3.3 PLANNING AND SCHEDULING ISSUES

In this section, we provide the Manufacturing Planning & Control (MPC) framework to classify current planning and scheduling activities. Also we provide more details regarding the planning and scheduling process and its complexity and uncertainty. Finally, we summarize the observed problems.

3.3.1 Classification of current planning and scheduling activities

The current planning and scheduling activities can be classified as ‘Shop Floor Scheduling & Control’ and ‘Resource Group Loading’. Next, we elaborate on these classifications.

[5] With the term ‘feeding’ we mean the supply of tires to the measuring machines. This term is often intertwined with the term ‘supply’.

Shop Floor Scheduling & Control

Regarding the planning and scheduling activities at the Uniformity department, mainly scheduling of jobs is performed. These activities can be classified as 'Shop Floor Scheduling & Control' since the activities correspond with the 'operational' and 'capacity planning' level (see Figure 13). The scheduling activities have to deal with the execution at the short term (operational) and are closely related to the use of capacity ('Capacity planning'). At this stage, no capacity flexibility is present; only time flexibility. This illustrates the impact of 'Resource Group Loading' on the scheduling activities.

Resource Group Loading

Besides the Shop Floor Scheduling & Control activities, Resource Group Loading takes place. The department of Organization is responsible for determining the required resources for various periods during the year, based upon the overall production planning. Most important decisions are made regarding the required size of the workforce. Besides this, this department calculates whether the capacity is sufficient for the various periods during the year. The above indicated activities, correspond to the quadrant of 'Resource Group Loading' activities, (also known as 'Rough-Cut-Capacity-Planning', see Figure 13) which takes place at 'tactical' and 'capacity planning' level. At this stage, both capacity and time flexibility is present.

As Hans et al. (2010) conclude, 'Resource Group Loading' planning decisions influence the scheduling activities at 'operational' level. We observed this by the restrictions at operational level when determining the workforce schedule and when selecting the jobs to be scheduled. We observe that scheduling of the jobs is often based upon the available workforce instead of other relevant criteria.

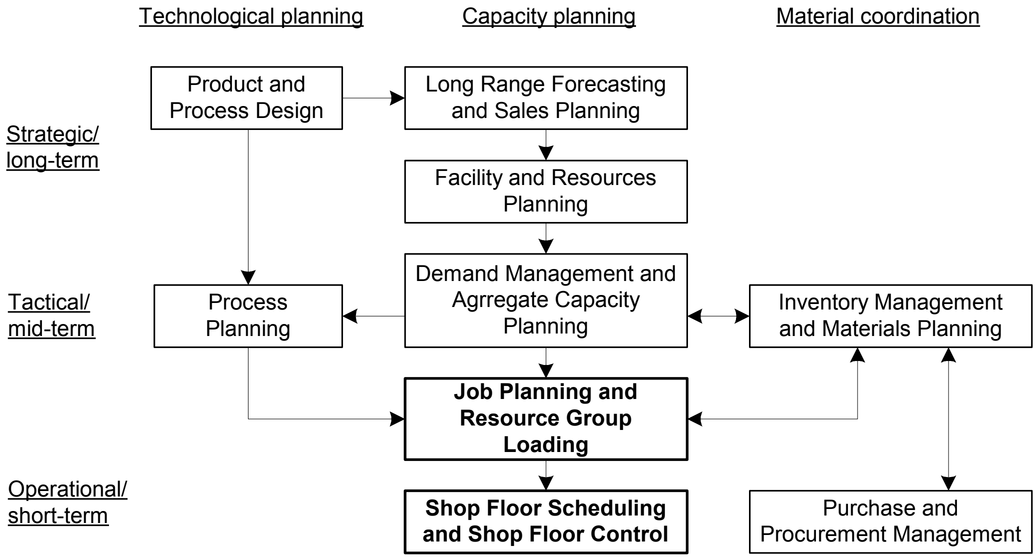

Figure 13: A manufacturing planning and control reference architecture Source: Zijm (2007)

3.3.2 Scheduling of orders

Next, we describe the scheduling process of both the X-ray and uniformity machines in more detail, after which we illustrate the complexity and uncertainty of this process.

Current scheduling process

For both type of machines (X-ray and uniformity), a separate schedule is set up by the ERP system. Based upon the current inventory levels of produced tires, a schedule is provided. The schedule consists of the following information: tire type, diameter size, number of tires to test, expected total measurement time, setup time, and the machine on which the machines have to be measured. The scheduling module takes into account that the tire types are first planned on the X-ray machine. After the X-ray measurement, the tires are transported back to the warehouse to be stored until they are scheduled to be measured on the uniformity machine.

An example of a schedule of both the X-ray and uniformity machines can be found in Appendix M.

Complexity & uncertainty of the scheduling activities

Because of precedence relations, different machine cycle times, setups, restricted capacity, and variability, the scheduling process can be labelled as complex and uncertain. Currently these aspects (except for precedence relations) are not taken into account nor managed properly. This is observable by the two separate schedules and by providing the schedules based upon basic elements as inventory level, diameter size and machine limitations.

Different machine cycle times of both types of measurements makes scheduling even more complex. Together with the limited buffering possibilities at the machines this limits the possibility of putting both machines right after each other (making the process more 'flow'). Next to that, setups have to be performed when switching to a different tire type. These influencing factors make the scheduling process complex. Also uncertainty is involved because of variability regarding 1) different type of tires (diversity) to be measured each day, 2) ad hoc activities breaking up the main activities (non-preemptive), and 3) variability due to the Quality Control System. This clarifies that setting up a robust schedule is very complex.

3.3.3 Problems observed

Interviews with various coordinators show that the current schedule, as provided by the ERP system, is hardly used. It is currently used as an overview of orders to be scheduled. The coordinator of each shift decides which order to schedule on which machine and at what time. This results in a schedule based upon personal insights and results in a planning horizon of eight hours instead of 24 hours (as desired by Apollo Vredestein based upon the expectation that a 24 hour planning is more efficient because of cooperation between shifts). This results in a lack of control; the activities at the Uniformity department cannot be influenced using the current planning. The current way of planning does not result in an efficient plan and can therefore be categorized as waste.

Decisions regarding the size of workforce are based upon average required workforce. This results in an allocated fixed amount of workforce not taking into account the required workforce during peak periods. This is an inadequate method and should be reconsidered.

We further investigate the impact of the lack of a proper schedule on operational performance in the remaining part of this research to indicate its contribution to the disappointing current performance. In Section 3.4, we determine direction for a more detailed analysis.

3.4 DIRECTION FOR A DETAILED ANALYSIS

Both Sections 3.2 and 3.3 have given an overview of the observed main problems. Based upon this result, we elaborate on these problems in more detail. Both the process and planning related problems are investigated in more detail.

Regarding the process related problems, we take into account the factors causing the low capacity utilization, the causes of idle time, the feeding of the machines, the impact of rework, and the lead time. Regarding the planning related problems, we investigate the impact of the complexity and uncertainty of the planning and scheduling activities. We investigate this in Section 4.2. In Section 4.2 we also investigate whether more factors influence the current performance. These factors are provided by creating an overview of the Uniformity department including various factors that might influence the performance. Based upon the impact and frequency of those disturbing factors, we determine the impact.

Based upon efficiency measurements, a VSM, and a planning framework, we analysed the current situation. We illustrated the impact of both the overall production planning and the measuring regulations. Also, we identified the bottleneck and illustrated that the measuring machines are a major factor influencing the throughput. The capacity utilization values show that the current use of the machines is relative low. Also efficiency indicators show the same result. Using a Value Stream Map, we identified and categorized efficiency losses into one of the seven types of waste. Next to these efficiency losses, the planning and scheduling activities are analysed resulting in the observation that the planning activities are complex and uncertain and contain variability. This results in a planning, provided by the ERP system, that is not used in practice. Section 3.4 has given an overview of process and planning related observed problems. Chapter 4 elaborates on these problems by analysing them in more detail.

CHAPTER 4 – ANALYSIS OF LOW CAPACITY UTILIZATION

In this chapter, we provide a more detailed analysis based upon observed efficiency losses as indicated in Chapter 3. Section 4.1 discusses the idle time of the measuring machines to illustrate the direct causes of observed idle time. Next, Section 4.2 provides an analysis regarding other factors influencing the (required) capacity utilization. This provides insight into the most influencing factors. Finally, we determine the root causes in Section 4.3 to provide direction for setting up solutions.

4.1 IDLE TIME OF THE MEASURING MACHINES

This section provides an overview of the amount of idle time, causing the low capacity utilization rate as illustrated in Section 3.2. We define idle time as the amount of time the machine is not measuring tires. Using direct observations (de Vaus, 2009), interviews, and data from the ERP-system, we analysed the amount of idle time during peak production periods. For reliability and validity purposes, we collected data during various shifts and time periods. Interviews have been organized among various employees, ensuring its multi-disciplinary character. The ERP-system has provided additional quantitative data.

First, Section 4.1.2 illustrates the total amount of idle time to show the amount of unused capacity. Next, we discuss the impact of rework on the machines. Rework does not lead to idle time but does require valuable capacity, reducing the amount of capacity remaining. In Sections 4.1.4 and 4.1.5, we set up idle time categories to categorize the observed idle time and we perform a chi-square test to determine the statistical significance of the collected data. Finally, we provide the observed idle time causes.

4.1.2 Total observed amount of idle time

Figure 14 provides an overview of the total amount of idle time of the measuring machines during peak production periods.

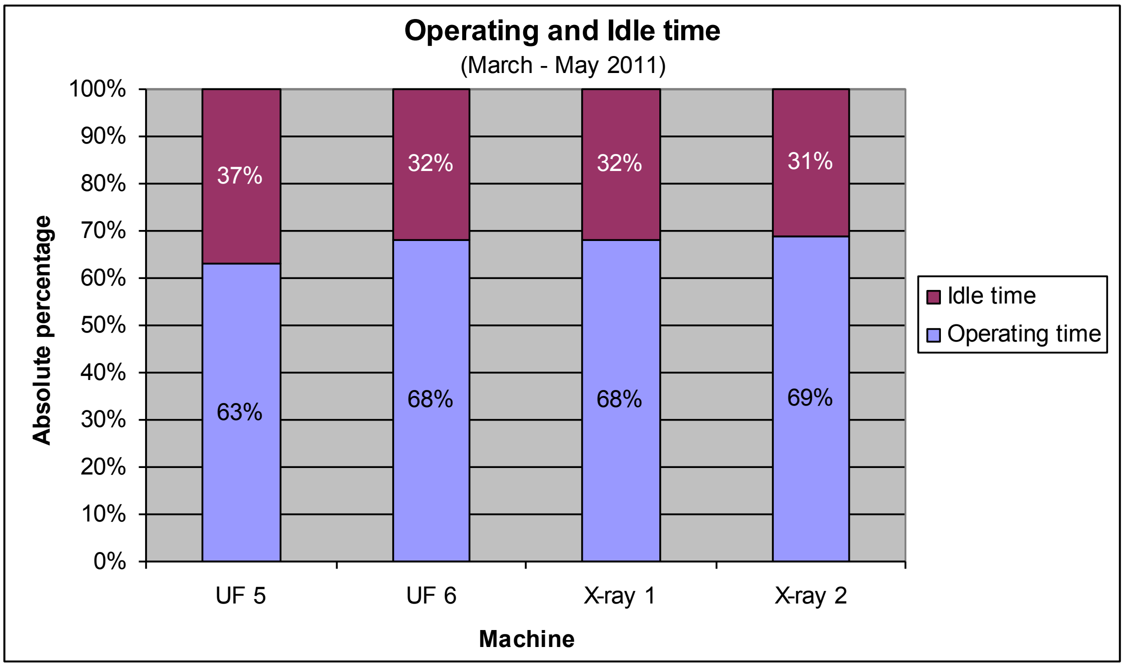

Figure 14: overview of operating and idle time during peak production periods

The figure shows that about 60% to 70% of the capacity is actually used to perform measurements. This is labelled as 'operating time'. During the remaining amount of time (about 30% to 40%), the machines are idle. These results correspond with the utilization rate as depicted in Section 3.2 (see Figure 10). This confirms the reliability and accuracy of the utilization figures by both showing the same figures. It should be mentioned that for both uniformity machines, 5% of the capacity is used for rework (re-testing tires). The X-ray machines do not require rework.

In Section 4.1.3 we briefly mention the impact of re-testing tires.

4.1.3 Impact of the amount of rework

We observe that at both uniformity machines 5% of the capacity is lost due to rework. Rework consists of re-testing activities of tires that are declined after being measured the first time. Once it turns out that a tire is declined, it is allowed to retest it once. Interviews with engineers turn out that the underlying reasons of re-tests mainly arise from machine measuring accuracy caused by machine calibrations and machine measuring variance. Various engineers from Apollo Vredestein conclude that the measuring variance is hard to reduce. It should be investigated further how these technical influences can be reduced. Due to the relative small amount of rework together with the technical causes, which are hard to solve, the amount of rework is not further investigated.

4.1.4 Idle time causes

As Figure 14 clarifies, we observe a lot of idle time. However, the causes of observed idle time so far remained unknown. To provide more insight in the factors causing the idle time, an observational study is performed. Using direct observing operator behaviour and machine status (uptime/downtime), we logged data (see Appendix N for the data collection form). In total, we performed 20 observations, each taking about 2 hours. During these observations, operator behavior has been monitored and, every 5 minutes, machine status has been logged. We have set up various idle time categories to correctly allocate the observed idle time into proper categories (see Table 2). We split up the idle time into preemptive and *non*-preemptive outages[6]. More details of the idle time categories can be found in Appendix O.

Type	Category	Subcategories
Preemptive outages	Machine failure	Robot machine failure Conveyor belt failure Measuring machine failure
Non-preemptive outages	Changeover activities	Changeover tasks Influence operator
	Setups	Conveyor belt and other setup tasks Influence operator Influence truck driver
	Swapping pallets	Influence truck driver
	Breaks	Influence operator
	Changing shifts	Influence operator
Additional outages	Operator unavailability (excl. breaks)	Influence operator
	Lack of expertise	Influence operator

Table 2: idle time (sub)categories

4.1.5 Statistical significance of collected data

To determine the statistical significance of the collected data, we have performed a chi-square test[7]. This test determines the statistical chance that the observations are representative. The result shows that the statistical significance of the total percentage of idle time equals about 97 – 99% whereas the statistical significance of the idle time causes equals about 80 – 89%. The high probabilities show its statistical significance and provide a reliable basis for further analysis. In Appendix P we provide a more detailed overview of the chi-square analysis.

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[6] Preemptive outages are disturbances that can occur at every sudden moment. *Non*preemptive outages are stoppages that occur between, rather than during, jobs (Hopp & Spearman, 2000).

[7] The chi-square test is a statistical test to determine to which extend the observed phenomenon matches with the (statistical) expectation.

4.1.6 Generalizability of collected data

Using the various idle time categories (see Section 4.1.4), we allocate the observed idle time. It should be noticed that the analysis only includes both uniformity machines, but not the X-ray machines. We made this decision due to time restrictions and limited available data. However, based upon the available data, direct observations, and interviews, we state that the observations are valid for both types of measurement machines. First of all, Figure 14 shows a similar utilization rate (about 68%) and a similar amount of idle time (about 32%) for both the uniformity and X-ray machines. Next, we observe that the supply system is exactly the same and mainly similar tasks are executed at both the uniformity and the X-ray machines. For both machines the order needs to be loaded to the machine and the robot (see Appendix Q). This process is similar. Furthermore, capacity utilization of the X-ray machine can be easily increased directly by assigning an operator full-time to this machine. This increases capacity utilization with at least (7% - 4%=) 3% (see Table 3).

	2 operators (% idle time due to **unavailability** cause)	3 operators (% idle time due to **unavailability** cause)
Observation 1	8%	5%
Observation 2	6%	4%
Observation 3	7%	4%
Observation 4	6%	4%
Average	**7%**	**4%**

Table 3: influence of the unavailability of operators

Finally, we observe that the operator responsible for the uniformity machine is often also responsible for one of the X-ray machines. He operates both machines simultaneously. This confirms that it is highly plausible that the main idle time causes observed at the Uniformity machine are also present at the X-ray machine.

We present the results of the idle time analysis next, in Section 4.1.7.

4.1.7 The result – categorized idle time

For both uniformity machine 5 and 6, we categorize the observed idle time into the idle time (sub)categories. In this section, we provide the results of the idle time analysis (see Figure 15 and Figure 16). The results are expressed in absolute percentages of (available) capacity[8].

[8] Here, we express capacity in available minutes each 24h where total capacity is equal to 100%

The main idle time causes, interacting with each other, are:

- Setups
- Swapping pallets (supply of tires)

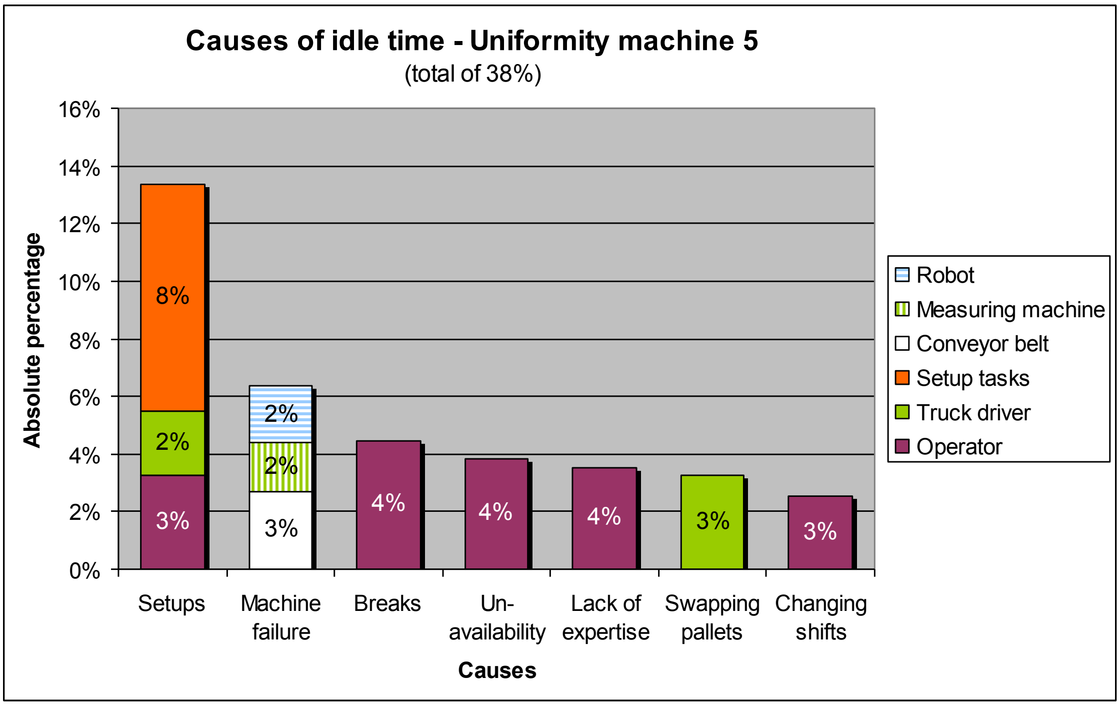

Figure 15: causes of idle time regarding uniformity machine 5

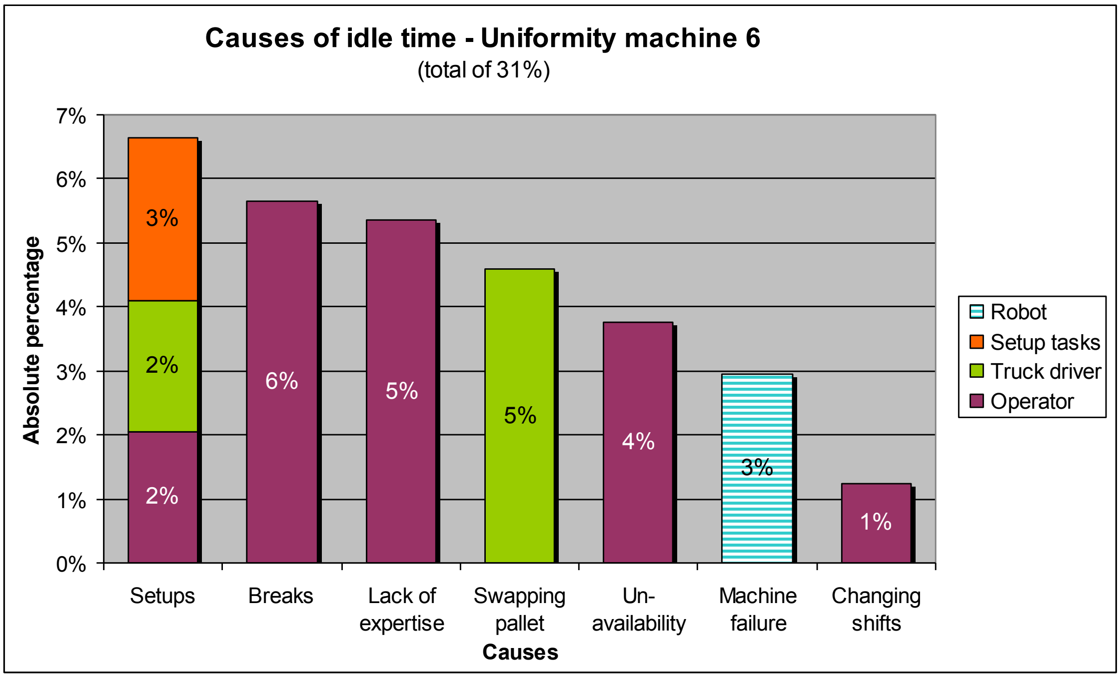

Figure 16: causes of idle time regarding uniformity machine 6

Idle time causes - uniformity machines 5 versus 6

We observe a difference in causes of idle time regarding uniformity machines 5 and 6. At uniformity machine 5 we observe 13% idle time due to setups, whereas idle time due to setups for uniformity machine 6 equals 7%. This difference occurs because most of the time (74%) uniformity machine 5 measures short series of various tires whereas uniformity machine 6 most of the time (91%) measures the larger series. This increases the amount of setups for uniformity machine 5. Next, we observe more machine failures at uniformity machine 5. This has mainly to do with the conveyor belt that frequently breaks down (see Figure 15). We observe another difference in the category 'changing pallet'. At uniformity machine 6, more idle time (5% + 2%) occurs during the swapping of pallets. This can also be explained since uniformity machine 6 measures larger series most. This means that the machine needs less setups, increasing the machine uptime. A delayed supply of tires immediately results in idle time. This illustrates the importance of in time supply regarding uniformity machine 6. The observed amount of idle time regarding 'breaks', 'lack of expertise', and 'unavailability' (see Figure 15 and Figure 16) is quite similar when comparing both machines. Besides this, it should be mentioned that X-ray machine 1 and 2 do not differ in the same way as both uniformity machines.

Minor changeover activities

The next thing that strikes us is that no idle time is observed due to changeover activities of flanges (due to different diameter sizes of tires). When determining the amount of changeovers during peak production periods, it turns out that uniformity machine 5 sporadically changes flanges. For uniformity machine 5, near 0% idle time is present due to changeover activities. For uniformity machine 6 this percentage turns out to be 3%. It is known that multiple advanced flanges[9] are ordered to significantly reduce the amount of changeover activities. Therefore we do not take changeovers into account any further in this thesis.

Next, in both Sections 4.1.8 and 4.1.9, we differentiate the observed idle time into two categories: 1) idle time caused by machine design and 2) idle time caused by operator influence. The first selection illustrates the impact of machine design on capacity utilization whereas the second selection shows how the capacity utilization is influenced by the operator.

4.1.8 Machine design limiting capacity utilization

In this section, we show how the capacity utilization is limited by inefficient machine design. The main machine design factors reducing the capacity utilization are setups, swapping of pallets, and machine failures.

[9] These flanges are able to measure various tires differing in diameter size without the need for a changeover.

Setups

Performing setups is required when a new order, containing tires with an equal diameter size, needs to be measured. During a setup, only adjusting machine settings are required. Setups cause the major part (7 – 13%) of observed idle time for both uniformity machines. First of all, several setting adjustments at various instrument panels need to be executed to perform a setup. The sequence of these tasks directly influences the time until the machine can continue to measure tires[10] and is therefore a critical element during the setup process. Besides this, the conveyor belt of the machine needs to be completely empty before machine and robot settings can be adjusted for a new order. This implicates that during each setup, at least 1 minute is lost because of the impossibility of setting up the machine while the current order is still being measured. Since each day (24h) about 40 setups are required, this adds up to (1 minute * 40 setups =) 40 minutes every 24 hours, contributing to 3% idle time. These two issues arise from inefficient machine design and contribute for the major part (3 – 8%) to the idle time during setups. This shows that improvement potential is present.

Since at uniformity machine 5 most setups need to be performed, the current design of setups influences this machine more than it influences uniformity machine 6.

Swapping pallets

Regarding the swapping of pallets, several issues can be allocated to the inefficient design of this process. First of all, the truck driver is visually noticed when a pallet needs to be swapped: a green light on the measuring machine turns on. At this moment, the machine is already idle. Therefore, this trigger is too late. When the truck driver can be noticed on beforehand, a more synchronized swapping of pallets can be realized. Besides this, due to the transportation activities from and to the Temporary Storage Area (TSA), the truck driver is not always around to see whether the light is green or not.

Minor buffering possibilities are present to feed the measuring machines. At most three pallets can be placed on the machine. It should also be mentioned that the robot, picking the tires from the pallets, needs to be temporary set on non-active when a truck driver swaps pallets. This also harms the supply of tires to the machine (1 – 2%[11]). When better buffering possibilities can be provided, the impact of swapping pallets declines.

For uniformity machine 6 the impact of the truck driver is clearly observable (7%). However, whereas the impact of the truck driver for uniformity machine 5 seems to be relatively low

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[10] Both robot- and machine settings need to be adjusted each new order. When first the machine is set up, while the tires are already available to be picked by the robot, the robot is idle, resulting in machine idle time. When first setting up the robot, the tires can be transported to the machine. During this time, the machine can be set up. Less idle time is present.

[11] As provided by norm-time calculations.

(5%), the following should be noticed. When reducing the required time for setups, the more accurate the truck driver needs to become to supply the machine just in time. Therefore, for both machines, the supply of tires should be improved.

Machine failure

Main machine failure is observable at the conveyor belt of the measuring machines. Various tire types cause problems with the conveyor belt of uniformity machine 5 (resulting in 3% idle time). This can be solved by correctly adjusting the conveyor belt. In the current situation, this is done by a variety of operators instead of a mechanic, resulting in bad adjusting the conveyor belt. This results in even more problems with the conveyor belt.

In total, machine redesign can reduce the amount of idle time by about 12% (setups: 3%, swapping pallets: 6%, and machine failures: 3%).

Next, we describe how capacity utilization is limited by operator influence.

4.1.9 Operator influence limiting capacity utilization

In this section we describe the lack of efficient use of the capacity, caused by the operator. This is observed at operational level and is caused by operators, truck drivers, coordinators, or the management.

Setups

Observing various operators[12] from different shifts shows that minor preparation of setup activities is present. Operators usually start acting at the moment they are triggered. This might be a machine that is idle or a truck driver supplying the amount of tires on the machine. Although in Section 4.1.7 we mention that the major amount of idle time during setups is caused by inefficient machine design, operator influence should not be neglected. Especially at uniformity machine 6, a lot of time during setups is caused by a lack of preparation. This can be shown by various large time gaps (15 minutes) during setups while we also observe (a few) smaller time gaps (< 5 minutes).

When comparing both uniformity machines, using ERP-data, we observe that uniformity machine 5 has about 35 – 45 setups each day, each taking 6 – 8 minutes. Uniformity machine 6 has significantly less setups (about 10 – 15) each day. However, each setup takes about 15 – 20 minutes. This is observed (using ERP-data) by the way both machines are used. Machine 5 is used to measure most small series, leading to the understanding that at this machine frequently setups need to be performed. Uniformity machine 6 measures most large

[12] In total, during 20 observations, about 15 different operators are observed. Using informal interviews, we investigated their way of working. From these results, we conclude that a lack of preparation is present.

series, leading to a minor focus on the setup process. This is confirmed by (informal) interviews including various operators from different shifts.

Swapping pallets

During the process of swapping pallets, the expertise of the truck driver has a direct influence. By observing various truck drivers during various shifts, it turns out that a more experienced truck driver is more pro-active[13], providing a more continuous supply for the measuring machines. Redesigning[14] the process of swapping pallets reduces the dependency of the truck driver. As also mentioned in Section 4.1.8, the supply of tires should be improved.

Robot failure

Frequently[15], an operator adjusting the instrument panel settings with wrong settings causes robot failure. More operator accuracy will contribute to the reduction of robot failure.

Breaks

Although the management requests to keep the machines running during breaks, we observe that the machines are often idle (4 – 6%). From multiple interviews[16] we state that this has mainly to do with the lack of motivation and understanding of the operators regarding the avoidance of idle time. Next to that, management does not seem to monitor and manage this properly since minor supervision is present.

Operator unavailability

Frequently, the machine is idle due to the absence of an operator (4%). In most cases, the operator is not alert enough to observe that the machine gets idle. This confirms the already mentioned lack of preparation and motivation. Interviews confirm that operators are not all aware of the importance of avoiding the machine getting idle.

Operator lack of expertise

Having various operators results in various levels of expertise. This becomes clear when observing the speed of acting and the degree of preparation. As most operators describe, the management has offered minor training. Only technical instructions, how to use the machines, are provided. No 'best practices' are present. This results in individual ways of operating and

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[13] This is observed by truck drivers preparing activities to realize a more continuous supply of tires.

[14] For example, triggering the truck driver on beforehand and/or providing better buffering possibilities will reduce idle time.

[15] Each two hour observation takes about 2 minutes at least caused by robot failure. This adds up to 1% idle time.

[16] At least 10 operators are interviewed regarding the consequences of idle machines and how, during breaks, the machines can be used in an optimal way.

results in 4 – 5% idle time. Clear work instructions and a standard way of working[17] should be present.

Changing shifts

Three times a day (each 8 hours), the next shift arrives. During this transition, machines are idle for some time (1 – 3%). We observe this idle time mainly just before the new shift arrives. This has to do with counting the number of measured tires, taking place about half an hour before the next shift arrives. Based upon these numbers, the current shift is judged. The remaining time of the current shift is perceived as unimportant, since during this time the current shift measures tires for the next shift. They are not judged based upon measuring tires during this last half hour.

In total, reducing the negative impact of operator influence can reduce the amount of idle time by about 12%.

A final remark regarding idle time is the way the operators and coordinators perceive idle time. When a machine at some point in time is idle for about one hour, everyone agrees on the fact that this is a loss of valuable amount of scarce capacity. However, when the machine is idle for 5 minutes at 12 different time points, no perception of waste is observed.

4.1.10 Conclusions

In Section 4.1 we have analysed the root causes of the observed amount of idle time. Based upon several (sub)categories the idle time has been allocated. The analysis results in the following conclusions:

- Idle time causes differ between the uniformity machines.
- Performing setups is a major issue (7 – 13%). Involved time needs to be reduced.
- Swapping pallets is a major cause of idle time for uniformity machine 6 (7%). For uniformity machine 5 the impact of swapping pallets increases (>5%) when increasing the uptime of the machine.
- The impact of the operator is shown in the idle time categories: ‘breaks’ (4 – 6%), ‘unavailability’ (4%), and ‘lack of expertise’ (4 – 5%). These causes are taken into account in Section 4.2.
- Machine failures contribute for 3 – 7% of the amount of idle time.
- Changing shifts (1 – 3%) is taken into account when providing solutions.
- Changeover activities are a minor issue (0 – 3%). Using advance flanges eliminates the necessity of changing flanges, reducing this percentage even more.

[17] By investigating ‘best practices’ an optimal way of operating can be introduced among operators.

Next to the direct observable idle time, other factors influence the (required) capacity utilization. In Section 4.2, we provide an overview of these factors. At that stage, various factors are combined into a multi-disciplinary overview.

4.2 OTHER FACTORS INFLUENCING THE CAPACITY UTILIZATION AND OUTPUT

Besides the idle time analysis, this section elaborates on other factors influencing the capacity utilization. Also during this analysis, we performed direct observations (de Vaus, 2009), interviews, and used data from the ERP-system. We take into account the interaction effects between factors and the corresponding consequences. Based upon this analysis and the already performed idle time analysis, we construct the overview of factors influencing the capacity utilization most.

4.2.1 Overview of factors

The overview of factors includes aspects regarding organizational issues, workforce planning and scheduling, measurement processes, transport processes, labelling processes, and tire aspects. In the figure we differentiate between main disturbing factors, which can be identified as causes, and main impact, which can be identified as the effect (see Figure 17).

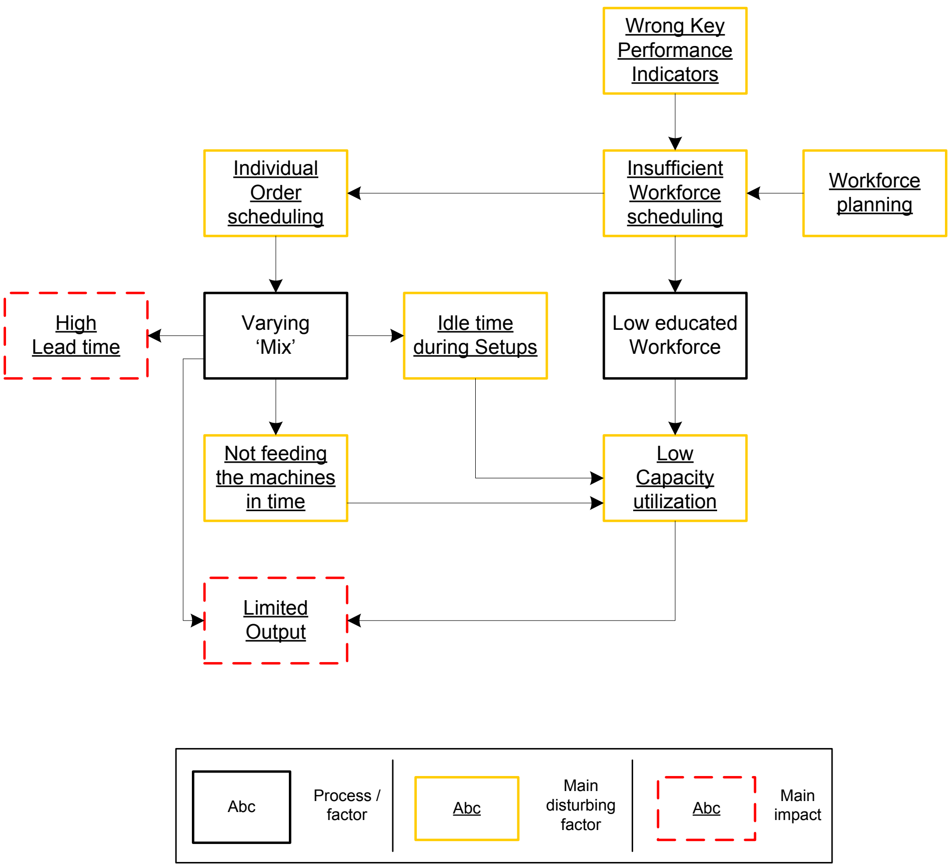

Figure 17: Overview of main disturbing factors influencing the capacity utilization and output

Figure 17 shows that both the capacity utilization and output of the Uniformity department is influenced by a variety of factors. In Appendix R we provide a full overview of all factors influencing the capacity utilization and output. It also includes a description for each factor. Next, in Section 4.2.2, we elaborate in more detail on the main relevant factors influencing the capacity utilization and output.

4.2.2 Main relevant factors influencing the capacity utilization

In this section, we determine the factors influencing the capacity utilization and output of the Uniformity department most. These factors are labelled as ‘main disturbing factors’ to indicate the main causes, see Figure 17. We include both qualitative and quantitative aspects in this argumentation.

We start with the argumentation why workforce planning and scheduling is one of the main relevant factors.

Insufficient Workforce Planning and Scheduling

As we conclude from the idle time analysis, a significant amount of idle time results from (lunch)breaks, operator unavailability, and lack of expertise. In total these factors contribute for 12 – 15% to the 31 – 38% observed idle time. This directly influences the capacity utilization of both the X-ray and uniformity machine. In the end, this influences the output of the Uniformity department. These factors are strongly related to workforce planning and scheduling, as we will explain next.

By determining the required number of operators and the required operator expertise, Workforce planning directly influences the scheduling of operators. We observe that usually two or three operators are assigned to the X-ray and uniformity machines. In case two operators are assigned to the machines, a lot of idle time is observed at both the X-ray and uniformity machines due to unavailability issues[18]. Assigning three operators reduces the amount of idle time with at least 4% of the observed 32 – 38%. Utilization figures show that both uniformity and X-ray machines require a high utilization. Therefore, a workforce with at least three operators for the machines is required during peak production periods.

Next to the amount of required operators, also the required expertise has to be taken into account during the workforce planning. As the idle time analysis shows, we observe idle time because of a lack of expertise. Given the fact that nearly no effort is spent on operator education and training, this is not surprising.

[18] Frequently an operator is required at one of the uniformity machines. During that time, the X-ray machine is immediately idle.

Finally, the workforce directly influences the feeding of the machines by the available number of truck drivers. This is restricted by the workforce planning, which implicates that no more than one truck driver is assigned to supply the machines. First of all, the idle time analysis shows that the truck driver causes 5 – 7% idle time. When increasing the uptime of the machines, the truck driver even becomes more busy, resulting in more idle time due to a late supply. This is already observed when comparing uniformity machine 5 with uniformity machine 6, see Figure 15 in Section 4.1.6. Capacity calculations from the department of Organization show that *on average* 4 truck drivers are required in total. During peak production periods, this amount should be assigned *at least*.

It should be mentioned that it is important to balance the workforce against the order requirements (Vairaktaris et al., 2002; Huang et al., 2009). Demand fluctuations ask for a dynamic workforce planning and scheduling (Hertz, 2010). It is known that the current workforce planning is static; a fixed amount of operators is assigned to the Uniformity department for the complete year. Since we observe large demand fluctuations, the workforce planning should be dynamic to ensure that, during peak production periods, the workforce is well balanced against the order requirements.

The above aspects show the relevance of workforce planning and scheduling, influencing the workforce occupation, capacity utilization, and output.

The above mentioned aspects can be summarized as follows:

- In total 12 – 15% of the observed idle time is influenced by workforce planning and scheduling causes. This impacts the capacity utilization and the output.
- During peak production periods, three operators are required at least to reduce the amount of idle time, increasing the utilization of the measuring machines.
- During peak production periods, in the current situation one truck driver is not sufficient to supply the machines.
- The expertise and knowledge of several operators is too low, causing idle time (4 - 5%).
- Nearly no effort is spent on training and education of the operators.
- The workforce planning is static, not including a dynamic effect from the varying workload.
- The workforce planning lacks a flexible component.

Next, we discuss the relevance of a proper scheduling component.

Individual Order Scheduling

Next to the workforce planning and scheduling, the orders need to be scheduled. When scheduling, the coordinator determines the 'mix' of tire types, which tires to measure when. It turns out that the 'mix' directly influences the utilization (varying from 53% to 70%) and output (varying from 3500 to 6000 tires each shift) of the Uniformity department (see Appendix S for figures). The output influences the inventory level. Since the amount of storage space is limited, the inventory level needs to be closely monitored. Also the 'mix' influences the supply of tires in the scenario where multiple orders, containing a low amount of tires on each pallet, are scheduled together. This implies that the truck driver has more transport activities to perform, resulting in (too) late supply.

In general, the scheduling decisions influence the lead time[19] of the tires (Leung, 2004). To determine the average lead time during peak production periods, we have collected data. See Table 4 for the results of the average lead time.

Year 2011	LEAD TIME (absolute percentage of total tires)			
	1 day	2 days	3 days	>3 days
March	27%	35%	18%	**21%**
April	23%	37%	17%	**22%**
May	23%	36%	13%	**29%**

Table 4: Average lead time of tires during peak production periods 2011 Source: ERP-data

As agreed with the Sales department, the maximum lead time equals three days. Table 4 shows that for 21 – 29% of the tires the agreed lead time is exceeded. This results in a due date delay for the customer, increasing the probability of harming customer satisfaction. Another major consequence: the longer the lead time, the less effective the quality feedback to production. This increases the probability of producing an unnecessary amount of non-quality tires. This is confirmed by process engineers from Apollo Vredestein.

Besides this, in the current situation, the schedule generated by the ERP system, is not used properly. This schedule provides the orders to be measured. Based upon this list, each coordinator determines a schedule based upon personal insights[20]. This can be explained by the fact that the provided schedule is static whereas practice shows uncertainty and unpredictability, asking for a more dynamic approach. This individual approach unfortunately leads to undesirable coordinator behaviour. This results in variability regarding output and utilization matters.

[19] With the lead time we mean the time between the arrival of the tires at the Uniformity department until the tires are measured.

[20] Since the planning is not sufficient, they set up a schedule for their shift based upon their view of 'good performance'

The complexity of scheduling, because of uncertainty, unpredictability, and prioritising aspects, makes the decision making process difficult. Interviews confirm that many coordinators struggle with making the optimal decision in various scenarios[21]. In the current situation, order scheduling is to a large extend based upon personal insights.

Finally, the scheduling decisions influence the workforce planning and scheduling by determining the staff workload (de Snoo, 2011). This dependency shows even more the relevance of a well-thought schedule, including a variety of relevant factors.

The above mentioned aspects can be summarized in the following way:

- Order scheduling determines the 'mix', which directly impacts the utilization and output (varying respectively from 53% to 70% and 3500 to 6000 tires each shift). High variation is present and sub optimal behaviour is observed.
- Order scheduling determines the lead time, which exceeds the agreed lead time in 21 – 29% of the cases during peak production periods.
- Order scheduling decisions are often based upon personal insights.
- Order scheduling interacts with the workforce planning and scheduling.
- (operational) Control is lacking.
- A dynamic scheduling component is missing.

Next, we mention the main impact of performance measurement.

Lack of proper Key Performance Indicators

Measuring performance has been proven as crucial to keep track of your processes (Artley & Stroh, 2001). This is often applied using Key Performance Indicators (KPIs). Well-defined KPIs directs people's behaviour, focuses attention on doing the right things, and makes performance visible (Artley & Stroh, 2001).

Besides the already mentioned problems regarding planning and scheduling, currently the Uniformity department lacks the right KPIs. This has a major impact on the performance of this department. Currently a KPI, being the output[22], is used by the coordinators and operators.

Each day, after each shift, the coordinators briefly report their performance to the production manager. Whereas coordinators start to realize that also other indicators are more important, including the amount of tires measured in relation to the available workforce, still the output remains a main criterion for the coordinators, influencing their decisions. This contributes to

[21] Multiple informal interviews with each coordinator turn out that most coordinators struggle with optimal decision making since a wide variety of factors needs to be taken into account. Minor decision tools are present.

[22] With the output we mean the total number of tires transported to the warehouse for final storage.

the undesirable coordinator decisions. It goes without saying that this lack of proper KPIs leads to a major impact on the use of the machines and on the output.

The influence of proper KPIs on the execution of setups, feeding of the machines, and regarding workforce scheduling should not be underestimated. This impacts both operational activities, including setups and supply, and workforce scheduling decisions. Using proper KPIs is inevitable when aiming for monitoring, controlling and improving the behaviour. Well-defined KPIs provide defined objectives and clear expectations, directs people's behaviour, and provides insight into current performance (Artley & Stroh, 2001).

High setup times

The idle time analysis has shown the amount of idle time caused by setups (7 – 13%). Also the various factors concerning inefficient machine design and the influence of both the operator and truck driver, contributing to the amount of idle time, are discussed. Finally, the impact of the idle time on the utilization is illustrated (see both Figure 15 and Figure 16).

In this section we discuss the way both Uniformity machines are used and on the impact of the required number of setups.

As mentioned in Section 4.1.6, in the current situation both uniformity machines are applied in a different way. Uniformity machine 6 is the machine with the shortest processing time. Besides this, machine 6 lacks the availability of advanced flanges reducing the ease of changeovers. This motivates to measure large orders with the same setup. For uniformity machine 5, the arguments are the other way around. Uniformity machine 5 has a slightly longer processing time compared to uniformity machine 6 but possesses advanced flanges. This eliminates the need for a changeover and motivates to measure small orders differing in diameter size. The decision, how to apply the two machines, significantly influences the number of setups. Whereas the decision to apply both machines in a different way (short vs. long runs) is a common decision (as Petrovic et al., 2008 and Haase & Kimms, 2000 describe), processes should be arranged to support this decision. Currently, this is not taken into account sufficiently. No standard work instructions neither workforce scheduling decisions are provided.

Next, we elaborate on the relevance of feeding the measurement machines in time.

Not feeding the machines in time

As turned out from the idle time analysis and interviews, a lack in timely supply to the machines results in idle time of the machines (5 – 7%). As already discussed, several issues regarding inefficient machine design and lack of expertise are mentioned.

It turns out that frequently[23] even a well-experienced truck driver is unable to manage timely supply. This can be confirmed by capacity calculations from the department of Organization. These calculations show that *on average* 4 truck drivers in total are required. During peak production periods, even more should be required. When combining the observation and the capacity calculations, we conclude that structural improvements are necessary to solve this part of the problem.

In Section 4.2, we illustrated the factors influencing the capacity utilization most. Next, in Section 4.3, provide the root causes to provide an overview of the main problems to be solved.

4.3 ROOT CAUSES OF OBSERVED PROBLEMS

This section provides an overview of the various root causes, causing the problems at the Uniformity department. Based upon these root causes, we set up appropriate solutions.

4.3.1 Lack of well-defined Key Performance Indicators

As we emphasized in Section 4.2, the lack of proper and well-defined KPIs influence the order scheduling activities, the workforce scheduling, the setups, and the supply. No clear expectations are present, no performance is made visible, and no behaviour is directed. This has a main impact on the proper use of the machines and on the output realized.

This factor influences most other 'main disturbing' factors and is a basic element when aiming for managing a department properly. Proper and well-defined KPIs are inevitable to manage the Uniformity department, providing monitoring and controlling possibilities. This makes the lack of KPIs a major root causes of the observed problems at the Uniformity department.

4.3.2 Lack of a proper scheduling component

The impact of the lack of a scheduling component is illustrated in a qualitative and quantitative way. Undesirable coordinator behaviour is observed and a lack of management control is present.

Undesirable coordinator behaviour

Undesirable behaviour by coordinators is observed regarding neglecting the utilization of the machines. This behaviour is mainly influenced by the currently used informal KPI and should be eliminated by introducing proper and well-defined KPIs. Also, a well-thought scheduling component should be provided to simplify the order scheduling decision making process.

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[23] For example when only a few tires fit on a pallet more transport activities need to be performed. During our observations, multiple times even a well experienced truck driver was not able to supply all machines in time.

Lack of control

A lack of control is present regarding the tire types to be measured. This implicates that also a lack of control is present regarding the lead time, capacity utilization, and the output.

Together with proper KPIs, an effective scheduling component increases the utilization of the machines and provides management control.

4.3.3 Operator influence and inefficient machine design

In total about 18% of the time, the machines are idle due to machine operator influence. In 5 – 7% of the time, the truck driver and the inefficient machine design are responsible for the amount of idle time. Together, the operator and truck driver reduce the capacity utilization for about 23 - 25%. Regarding the inefficient machine design of the setups, the capacity utilization is reduced by another 10 – 13%.

Negative operator and truck driver influence

The amount of available workforce significantly influences the utilization of the measuring machines. The amount of machine operators should be at least three, whereas a single truck driver to supply the machines is not sufficient in several cases during peak production periods. The expertise and proactive attitude of both the operator and truck driver should be improved.

Inefficient (machine) design

Inefficient machine design regarding the setups causes idle time and should be improved. Required tasks to perform a setup should be reduced to a minimum. Also during the swapping of pallets, inefficient design is observed. In the current situation, buffering possibilities are limited.

At operational level, these factors directly influence the amount of idle time, harming the utilization and output of the Uniformity department.

In Chapter 4, we have performed an analysis regarding idle time causes and main factors influencing the capacity utilization and output. We identified the major root causes of the problems at the Uniformity department. First of all, currently the right set of KPIs is missing. Together with the absence of proper KPIs, the lack of a proper scheduling component results in undesirable coordinator behaviour and a lack of management control. Furthermore, the influence of both the operator and truck driver turn out to be decisive regarding the idle time analysis. Also observed inefficient machine design contributes to a disappointing capacity utilization and output. We take these root causes into account when providing solutions in Chapter 5.

CHAPTER 5 – SOLUTIONS TO INCREASE CAPACITY UTILIZATION

Based upon the analyses, we defined root causes of the low capacity utilization and output. This chapter provides solutions to significantly improve the situation. The overall goal is to increase the current capacity utilization (see Section 1.4). First, in Section 5.1, we provide an overview of the performance gap in 2012 to be solved. Next, Section 5.2 describes the brainstorm session with relevant people, organized with the purpose of generating ideas to solve the root causes. In that section and in Section 5.3 we reduce the number of ideas using selection criteria. In Section 5.4, we provide well-developed solutions containing the most potential. In Section 5.5 we determine criteria after which various potential solutions are ranked upon these criteria. We performed a sensitivity analysis to examine the robustness of the results. Section 5.6 provides suggestions regarding the implementation of the solutions. Finally, we provide conclusions in Section 5.7 regarding the best solution(s) to overcome the problems as currently observed during peak production periods.

5.1 PERFORMANCE GAP IN 2012

With the performance gap we mean the difference between current capacity utilization and the internal determined target. This provides a clear target and thereby direction for developing solutions. To determine the performance gap, we compare the current capacity utilization with the target capacity utilization. In Section 4.1 we already identified the current capacity utilization. Besides this, the target capacity utilization is based upon the production planning during peak periods for the coming year 2012. Using well-established standard times, as set up by Apollo Vredestein, we calculate the target capacity utilization during peak production periods. These calculations turn out to be realistic since 1) the production planning is executed mainly as planned, implying a high level of predictability and 2) the standard times are up-to-date. In Table 5 we illustrate the comparison of both the current and target utilization, providing the performance gap.

Machine	Current capacity utilization	Target capacity utilization (2012)	Performance gap
UF 5	63%	74%	**11%**
UF 6	68%	80%	**12%**
X-ray 1	68%	89%	**21%**
X-ray 2	69%	88%	**19%**

Table 5: overview of the performance gap

It turns out that the performance gap of both uniformity machines are about 10% whereas the X-ray machines lack about 20% performance. To bridge the performance gap, we use the results of the idle time analysis. We distinguish between technical and workforce related improvement potential. Well-designed and well-applied technical solutions have a high chance for success and reduce the dependency of (negative) operator influence (Kotter, 1995). This is desirable since workforce related efficiency losses turn out to be relative hard to solve (Kotter, 1995). However, the large amount of efficiency loss due to operator influence makes the improvement potential significant.

Based upon the idle time results and standard times, as set up by Apollo Vredestein, in Table 6 we present the improvement potential. For the workforce related potential, this is based upon 50% from the potential identified by the idle time analysis. This is based upon 1) the literature which states that workforce related losses are hard to solve and 2) interviews[24] indicating that about 50% of the operators is open for change (limiting to obtain full potential). For the technical related potential, full potential as identified by the idle time analysis is feasible. This is realistic since well-designed and well-implemented solutions will obtain full potential (Kotter, 1995). Detailed calculations can be found in Appendix T.

	TECHNICAL				WORKFORCE								
Machine	Setups	Supply	Machine failure	**Total technical**	Setups	Supply	Unavailability	Breaks	Lack of expertise	Changing shifts	**Total workforce**	**Overall potential**	**Performance gap**
UF 5	4%	6%	3%	**13%**	2%	1%	2%	2%	2%	2%	**10%**	**23%**	11%
UF 6	1%	6%	2%	**9%**	2%	1%	2%	3%	3%	1%	**10%**	**19%**	12%
X-ray 1	2%	5%	2%	**9%**	1%	1%	6%	3%	2%	2%	**13%**	**22%**	21%
X-ray 2	3%	5%	2%	**10%**	1%	1%	6%	3%	2%	2%	**13%**	**23%**	19%

Table 6: technical and workforce related improvement potential

Table 6 shows that the performance gap can be bridged. For the uniformity machines, only realising the technical potential will be sufficient to bridge the performance gap. Together with the workforce related improvement potential it seems realistic to expect that the performance gap can be bridged. However, for both X-ray machines also workforce related improvement

[24] Operators have been interviewed by asking questions regarding their openness for improvements and change. These interviews show that about half of the operators is open for change.

potential is required. Since the total improvement potential is only slightly larger than the performance gap, more attention will be required to realize the improvements.

5.2 IDEA GENERATION FOR SOLVING OBSERVED IDLE TIME CAUSES

To solve the root causes as depicted in Section 4.3, in this section we describe the idea generation process. This process is applied as starting point for solutions. By using both theory and organizing a brainstorm session with relevant people, ideas have been generated. We organized the brainstorm session to ensure a high level of acceptance regarding the generated ideas. We involved various disciplines[25], ensuring its multidisciplinary character, and stimulated creativity. We applied the following brainstorm rules (Koberg and Bagnall, 2003): 1) postpone feedback, 2) the more ideas the better, 3) stimulate creativity, and 4) stimulate improving ideas of others. For each idle time cause we generated ideas by writing them down, one by one. After multiple sessions, together with the involved people, we categorized the generated ideas into a grid containing the variables 'complexity' and 'effectiveness'. Based upon this grid, we ranked the outcome of the brainstorm session to select the most potential ideas. Feedback from the involved people on the results is applied. Next, we show the selection of most potential ideas whereas Appendix U provides all generated ideas.

- Improve preparation of tasks
- Reduce number of setup tasks
- Improve communication
- Improve expertise by training
- Increase buffering possibilities
- Reduce machine failures
- Introduce better KPIs
- Increase robot-intelligence
- Improve current planning
- Improve supply
- Prioritise machines
- Provide a better schedule
- Increase maintenance
- Increase education
- Alarm when machine gets idle
- Provide enough operators

We have provided additional literature research regarding the root causes. This has lead to an increased amount of insight into these aspects. This is used to strengthen and extend several of the generated ideas.

[25] We involved process engineers, engineers, mechanics, production managers, and industrial engineers.

5.3 CONSTRAINTS FOR GENERATED IDEAS

Before elaborating on solutions, we describe the constraints to be taken into account. Using these constraints we made a selection of the highly ranked ideas, as generated by the brainstorm session. These constraints are also taken into account when developing solutions in more detail.

- Limited amount of available space. *Solution needs to cope with available space*
- No complete redesign of the Uniformity department. *Complete redesign, including factory layout, is out of scope due to time restrictions*
- Uniformity department has to cope with uncertainty and variability. *Solution needs to fit within a dynamic environment*
- Current workforce. *Solutions need to cope with the existing workforce*
- Major investments are excluded. *Major required investments are out of scope due to the opportunity costs of buying an additional measuring machine*[26]

5.4 SIX POTENTIAL SOLUTIONS FOR INCREASING CAPACITY UTILIZATION

The selected solutions arise from the brainstorm session. First, constraints (see Section 5.3) have been applied to the limit the generated ideas. Next, we ranked the selection of remaining ideas using the two criteria: 'complexity' and 'impact'. Based upon this ranking, six highly ranked potential solutions (from the initial selection, see Section 5.2) remain. These solutions contain both technical and workforce related improvements and cover the following problems: long setups, too late supply, machine failures, (negative) operator influence, lack of proper KPIs, and lack of a dynamic scheduling component.

An interaction effect is present between the setup- and supply process. The setup process includes supply activities, which need to be synchronized with the setup process. A truck driver arriving too late at a machine performing a setup leads immediately to idle time, although the setup process has been adjusted. Although implementing one of those technical solutions will contribute to a better performance, the best result will be obtained when changing both the setup- and supply processes simultaneously.

Next, we elaborate on the six potential solutions. For each solution, the overall goal and focus is mentioned to provide direction.

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[26] Buying an additional measuring machine solves the capacity problem. If investments are higher than the investments of buying a new machine, they will not be accepted by the management.

Solution 1: Improving machine setups and supply

Goal: reduce setup time to an absolute minimum

Focus: reduce required tasks to perform a setup

enable the machine to load multiple orders

improve timely supply

provide training to instruct operators and truck drivers

This solution arises from the significant amount of idle time during setups. Both technical and workforce related improvements are required to reduce the amount of idle time during setups. First of all, machine redesign is necessary to make this solution successful. By adjusting the existing software of the measurement machine, it can be adapted to enable loading multiple orders. This adjustment eliminates the necessity of the machine to be completely empty before a new order can be loaded, eliminating idle time. This solution includes supply improvements by redesign the supply process. This can be done by providing more buffering possibilities to ensure continuous supply. This can be realized for example with a conveyor belt, supplying the tires to the machine. The truck driver should be noticed in advance to stimulate in time supply. This can be realized for example by applying an indicator light on each truck to notify the truck driver when a pallet needs to be swapped. This will result in more in time supply. Operators and truck drivers need to be instructed properly about this new system to make the solution successful. Also proper preparation by the operator and truck driver, including pro-active behaviour, is required to gain full potential. A SMED[27] project is a suitable project structure for improving the machine setups and supply. Using this project structure, operators are involved and required tasks to be performed during a setup are identified. The goal for this project is to reduce machine idle during setups to a minimum. This solution reduces about 11% idle time (by adding up the improvement potential of categories 'setups' and 'supply', see Table 6).

Solution 2: Reducing machine failure

Goal: reduce total idle time caused by machine failure

Focus: provide a robust solution for the conveyor belt failure

This solution eliminates idle time due to machine failure. The analysis has shown that machine failure mainly occurs at uniformity machine 5 and X-ray machine 2. When introducing a more robust solution for the conveyor belt, it is expected to increase the capacity utilization significantly within a short time period. Multiple engineers of Apollo Vredestein mention two solutions: 1) more frequently maintenance or 2) invest in a completely new system. About 3% idle time is reduced by implementing this solution (see Table 6).

[27] Single Minute Exchange of Die (SMED) is a Lean Manufacturing method with the purpose of quickly and efficiently performing setups.

Solution 3: Providing proper scheduling component

Goal: ensure proper scheduling at the Uniformity department

Focus: include dynamic elements such as available workforce

This solution should contain a dynamic element, which is able to adapt to varying circumstances. Order scheduling determines the 'mix', the lead time, the output, and the capacity utilization. This leads to an increased control regarding these aspects. It should be further investigated whether this should be integrated in the ERP-system or whether providing new guidelines, simplifying the scheduling decisions, is more suitable for the current situation.

Solution 4: Introducing Key Performance Indicators (KPIs)

Goal: develop well-defined Key Performance Indicators

Focus: determine the right KPIs providing the actual performance
make a distinction between KPIs at operational and tactical level

Well-defined KPIs make performance visible, provide a clear goal, and direct people's behaviour. Proper KPIs should be developed, providing the relevant indicators for measuring performance. We recommend to start implementing 'utilization' as KPI, next to the already existing 'output'. Utilization provides direct insight in the use of the machines whereas 'output' gives information whether the output of tires is enough[28]. Utilization can be extended to Overall Equipment Effectiveness (OEE) to provide even more insight in the capacity utilization of the machines including efficiency losses (availability-, performance-, or quality losses). After proper KPIs have been defined, these can be implemented in quite a short time period. The result: direct indication of actual performance and objectives to reach. Based upon this information, the management will be aware of the current performance and is able to provide feedback. Besides this, the operators will be aware of their current performance. Before introducing a KPI, it should be ensured that the definition and meaning of the KPI is clear and adopted by the coordinators of each shift. The KPIs should support other improvement measures. It should be further investigated which set of KPIs are most suitable for the Uniformity department.

Solution 5: Providing education and training

Goal: increase expertise, stimulate pro-active behaviour

Focus: develop best practices, thereby using the capacity in an efficient way

This solution arises from the direct impact that operators have on the efficiency of processes. The analysis clearly shows this by idle time occurring because of lunch breaks, a lack of

[28] The KPI 'output' is based upon the phenomenon that to avoid increasing the inventory levels, output should equal input.

expertise, and during changing shifts. All directly influenced by the operator. Also a lack of motivation and preparation has been noticed. This solution includes the participation of operators to construct best practices. Best practices lead to operating more efficiently and create an adopted collective way of working. For motivation purposes, incentives may be applied. Using the (machine) capacity in an optimal way, by standardizing work instructions, is the main goal of the provided training. Furthermore, general training should be provided regarding continuation of measurements. About 7% idle time is reduced by implementing this solution (add up improvement potential of categories 'breaks', 'lack of expertise', and 'changing shifts', see Table 6).

Solution 6: Temporarily increasing the workforce

Goal: ensure a sufficient amount of workforce to increase machine uptime

Focus: sufficient amount of well-skilled machine operators

sufficient amount of well-skilled truck drivers

This solution is set up due to the impact of the available amount of workforce. By providing additional well-skilled (machine) operators and truck drivers, the workforce size can be temporarily increased. This shrinks idle time and increases capacity utilization. It should be mentioned that an interaction effect can be observed with the other proposed solutions. When for example a the setup- and supply process is improved, the influence of the operator shrinks, reducing the potential of temporarily increasing the workforce. However, temporarily increasing the workforce can increase the capacity utilization in a short time period and is therefore a valuable alternative solution. This increases idle time by about 5% (see Table 6 category 'Unavailability').

Next, these solutions are ranked upon selection criteria and weights using a Multi-Criteria Decision Analysis (MCDA).

5.5 MULTI-CRITERIA DECISION ANALYSIS FOR POTENTIAL SOLUTIONS

This section provides a Multi-Criteria Decision Analysis, which is set up to rank the various potential solutions (see Section 5.4) upon relevant criteria. We use the Simple Multi-attribute Rating Technique (Goodwin & Wright, 1991) for its simplicity and transparent analysis. According to the provided step-by-step process, first we describe how we construct the criteria and the weights. Next, we rank the solutions by providing a specific scoring method. Finally, we provide a sensitivity analysis to examine how robust the results are.

5.5.1 Selection of criteria and weights

By interviewing various Apollo Vredestein employees, we set up criteria. These criteria are compared with decision making criteria provided by the literature. When merging the criteria, we take into account the requirements for setting up criteria as determined by Keeney & Raiffa (2003). Criteria need to be complete, non-redundant, operational, independent and that the amount needs to be limited (Keeney & Raiffa, 2003). For more details, see Appendix V. Also the weights of the criteria have been determined by various interviews with decision making managers of Apollo Vredestein.

Determination of criteria

Based upon the provided input, we construct the following criteria:

- Improvement potential – *Expected capacity utilization increase*
- Costs – *Required resources*
- Ease of acceptance – *Degree of operator acceptance*
- Implementation time – *Time scope in which the solution can be implemented*

As Keeney & Raiffa (2003) put forward, the criteria need to be independent. Whereas no direct relation is present between the criteria, slight correlation might be present. However, correlation does not imply a direct relation and we take correlation into account by performing a sensitivity analysis.

When setting up categories we apply the four-point scale, as set up by Harris (1961) (see Table 7). This stimulates the decision maker to express a clear judgement. The improvement potential of the solutions can be quantified using absolute percentages of the capacity[29]. Also the criterion 'implementation time' can be quantified. For the other criteria qualitative criteria have been applied. The scale has been set up in such a way that a differentiated and well spread scoring exists. Table 8 shows that for each criterion the scores have a wide range (scores differ with at least 2 points) except for the criterion 'costs'. All potential solutions require less or more the same level of investment. Also this criterion has the lowest weight (15/100). Therefore, this will not harm the ranking process.

Since the criteria 'costs' and 'ease of acceptance' are represented in a qualitative way, we mention the motivation of the various categories (1 – 4). With 'high costs' we mention large investments to be approved by the management of Apollo B.V. (located in India). 'Major costs' are costs to be approved by the management of Apollo Vredestein B.V. 'Minor costs' are costs that can be easily approved. Regarding the 'ease of acceptance', with 'full resistance' we mention all operators disagreeing with the proposed solution. With 'common resistance' we

[29] Where total capacity is equal to 100%

mean the amount of resistance which can be observed when improvements take place. ‘Partially resistance’ is when only a certain amount of the operators disagree with the proposed solution. Based upon these definitions, the potential solutions are scored.

Determination of weights

Using interviews, the various decision makers have ranked the criteria by dividing 100 points among the various criteria, based upon their personal perception of importance. Given the short time period in which significant improvement potential needs to be obtained, these weights are reasonable. The weights are allocated as follows:

		SCORE			
Criterion	**Weight**	**1**	**2**	**3**	**4**
Improvement potential	**40**	< 5% (low)	5 – 10% (moderate)	10 – 15% (high)	>15% (very high)
Costs	**15**	high	major	minor	none
Ease of acceptance	**15**	full operator resistance	common operator resistance	partially operator resistance	no operator resistance
Implementation time	**30**	Within 7-12 months	Within 4-6 months	Within 2-3 months	Within 1 month

Table 7: overview of criteria, weights, and categories

In Section 5.5.2, we rank the potential solutions using the criteria and weights.

5.5.2 Ranking

		POTENTIAL SOLUTIONS					
Criterion	Weight	1	2	3	4	5	6
		Improve setup and supply (+/- 11%)	Reduce machine failure (+/- 3%)	Provide scheduling component	Introduce KPIs	Provide training (+/- 7%)	Temporarily increase workforce (+/- 5%)
Improvement potential	**40**	3	1	3	3	2	1
Costs	**15**	2	2	2	3	2	3
Ease of acceptance	**15**	3	4	2	2	1	4
Implementation time	**30**	2	3	2	3	2	4
Total score		255	220	240	285	185	265
Ranking		3	5	4	1	6	2

Table 8: scoring of potential solutions

Using the results of the analysis, having various interviews, and based upon various literature, we scored the potential solutions upon the criteria. It strikes us that, although a KPI is a supporting solution, this solution turns out to be ranked as best. This solution scores 20 points higher than the second ranked solution. For the remaining solutions, the differences between the scores differ less (except for the lowest ranked solution).

Next, we discuss the main difference of scores between the six defined solutions, starting with the criterion ‘improvement potential’. Solutions 1, 3 and 4 score ‘high’ (or 10 – 15%) on this criterion. The improvement of the setup- and supply process already has shown its improvement potential of 11%. It has been addressed that proper scheduling and well-defined KPIs have a major impact on the performance of the Uniformity department. Therefore the improvement potential is categorized as ‘high’. The idle time analysis has shown that the improvement potential regarding machine failure is about 3% and is therefore scored as ‘low’. Because of the human aspect, training results in moderate (7%) improvement potential. Changing people’s behaviour is difficult, however not impossible. When temporarily increasing the workforce, a temporary capacity utilization increase (+/- 5%) can be obtained but it does not structurally solve the problem at the Uniformity department.

Regarding the criterion ‘costs’, we ranked the solutions upon the expected required investments. The improvement of supply and setup and reducing machine failure requires technical adjustments. Besides this, both the scheduling and the KPIs require investments in terms of preparation time. However, whereas the scheduling might require investments in software, the KPIs can be introduced without any large investments. Providing training requires a significant amount of time and effort and is therefore ranked as ‘major costs’. Temporarily increasing the workforce involves ‘minor costs’ since temporary employees can be engaged.

The ‘ease of acceptance’ is based upon the expected operator acceptance. Because of mainly technical adjustments, for both setup and supply improvements and reducing machine failure acceptance will be obtained. In general, it is difficult to create acceptance and guarantee the ease of use regarding the scheduling component. All relevant aspects need to be modelled properly to make this solution successful, which is not easy. In general, KPIs are hard to implement due to the inevitable aspect to agree upon the most relevant performance criteria. It will not be easy to realize high acceptance. However, since the decision makers at Apollo Vredestein are convinced that the current KPIs are not sufficient, the ease of acceptance slightly increases. Providing training is scored as ‘full operator resistance’ since changing people’s behaviour seems to be hard as expected by Apollo Vredestein management. Natural resistance from the workforce against change is inevitable, asking for frequently monitoring operator behaviour. Temporarily increasing the workforce is not that difficult since this already has been applied frequently.

The scores regarding the criterion ‘implementation time’ differ in the following way. The setup and supply improvements can be realized within 4 – 6 months. Technical adjustments are required, consuming a significant amount of time. Also a scheduling component can be realized within the same time span. Providing training is ranked with a ‘2’ for the reason that it is expected that full improvement potential can be obtained within 4 – 6 months. Changing behaviour is not easy. Reducing machine failure can be realized within 2 – 3 months since only a technical solution is required from which the underlying causes are already known. Developing and implementing KPIs can be realized within 2 – 3 months. Whereas further research regarding proper KPIs will consume time, the implementation can be set up in a relative short time period. Finally, temporarily increasing the workforce is ranked with a ‘4’ since the amount of workforce can be increased within a short time period. When the management agrees upon this request, immediately action can be undertaken.

To determine the robustness of the outcome, we perform a sensitivity analysis. For each criterion we vary the weight (see Table 9).

Criterion	Weight			Scores and rankings					
	From	To		Improve setup and supply 1	Reduce machine failure 2	Provide scheduling component 3	Introduce KPIs 4	Provide training 5	Temporarily increase workforce 6
Improvement potential	40	30	Score	225	210	210	255	165	255
			Rank	**3**	**5**	**4**	**1**	**6**	**2**
		50	Score	285	230	270	315	205	275
			Rank	**2**	**5**	**4**	**1**	**6**	**3**
Costs	15	5	Score	235	200	220	255	165	235
			Rank	**3**	**5**	**4**	**1**	**6**	**2**
		25	Score	275	240	260	315	205	295
			Rank	**3**	**5**	**4**	**1**	**6**	**2**
Ease of acceptation	15	5	Score	225	180	220	265	175	225
			Rank	**3**	**5**	**4**	**1**	**6**	**2**
		25	Score	285	260	260	305	195	305
			Rank	**3**	**5**	**4**	**1**	**6**	**2**
Implementation time	30	20	Score	235	190	220	255	165	225
			Rank	**2**	**5**	**4**	**1**	**6**	**3**
		40	Score	275	250	260	315	205	305
			Rank	**3**	**5**	**4**	**1**	**6**	**2**

Table 9: results of the sensitivity analysis

Table 9 shows that, although adjusting the allocated weights of the criteria, solution 4 ('introduce KPIs') remains most highly ranked. Also the rankings of solutions 2, 3, and 5 remain unchanged. When adjusting the weights of criteria 'improvement potential' and 'implementation time' the rankings of solution 1 and 6 change. However, since the scores between these solutions differ minimal, no significant other insight in rankings is obtained. Since solution 4 is ranked most highly and the rankings of the other solutions also mainly keep unchanged, the sensitivity analysis has proven the robustness of the results. See Appendix W for the full calculations.

Since solution 4 scores high on almost every criteria, it is not surprisingly that it turns out best in every case. However, when adjusting the weights of 'improvement potential' and 'ease of implementation', solution six reaches the same score as the first ranked solution. This shows that the rankings of these solutions do differ minor in these two cases.

The scores from Table 8 show that introducing KPIs can be ranked as best solution followed by the scheduling component and the improvements of the setup- and supply process. Next, we provide suggestions for implementing the solutions.

5.6 IMPLEMENTATION OF SOLUTIONS

We recommend executing all provided solutions to bridge the performance gap. However, since the solutions differ in improvement potential, required resources, and time horizon, we provide the following implementation plan.

Within a short time period (January 2012), peak production periods for the year 2012 arise. Therefore, we recommend to prioritise the potential solutions. By analysing the expected improvement potential obtainable within a short time period, priority can be determined. Based upon this outcome, it can be determined how thorough each project needs to be executed. For example, it might be more effective for the short term to start introducing only one or two proper KPIs instead of developing a comprehensive configuration of KPIs to be implemented in the long term. For the medium- and long-term we recommend to introduce a well-structured education and training programme to increase expertise and including pro-active operator attitude. It should be mentioned that although prioritising is required, all solutions needs to be executed to bridge the performance gap.

The provided solutions interact with each other and contain a multi-disciplinary character since multiple departments are involved during the implementation of the solution. Therefore, we recommend organizing the implementation of the potential solutions by coordinating this implementation process by a single person. This way, progress of the various projects can be monitored centrally and interaction effects can be taken care of.

For a successful implementation, it is inevitable to provide clear communication towards all involved people, including: production managers, coordinators, and operators. Without proper communication the implementation, including ensuring potential, will be hard. Also managerial competences are required to realize the improvement potential. The management should provide clear objectives and feedback to improve the operations at the Uniformity department. Furthermore, it is known that workforce related improvements do require a kind of culture change. Since significant changes should be implemented, operators and coordinators should be involved during this process.

5.7 CONCLUSIONS

We have shown that the total performance gap (9 – 21%) can be bridged by both technical (9 – 13%) and workforce related improvements (10 – 13%). We have performed a brainstorm session to construct various solutions for the capacity utilization problem. Using criteria and constraints, the proposed solutions have been limited to six potential solutions. Using the

Simple Multi-Attribute Rating Technique we executed a decision analysis. The potential solutions have been prioritised using specific criteria and weights. The sensitivity analysis shows that the results are robust. We conclude that all solutions need to be implemented to bridge the performance gap.

In Chapter 5, we have provided solutions for solving the capacity utilization problem. Both technical and workforce related improvements have been developed. In Section 5.1, we have identified the performance gap 2012 to be bridged. Next, in Section 5.2, we described the process of idea generation with the purpose of providing solutions. Using criteria and constraints, most potential solutions have been selected. In Section 5.4, we further developed these solutions into concrete solutions containing a well-defined goal and focus. Using a Multi-Criteria Decision analysis, in Section 5.5, the solutions have been ranked upon relevant criteria. In Section 5.6 we have provided implementation recommendations of the solutions. We conclude that all six potential solutions need to be implemented to bridge the performance gap. In Chapter 6 we provide final conclusions of the research and recommendations.

CHAPTER 6 – CONCLUSIONS & RECOMMENDATIONS

In this chapter we provide conclusions and feedback of the research and recommendations. In Section 6.1, we provide conclusions by answering the main research question. Next, Section 6.2 provides reflection on the research. We elaborate on the recommendations regarding items outside the current research scope and suggestions regarding future research in Section 6.3.

6.1 CONCLUSIONS

The main research question, as defined in Section 1.3, was: *"In which way can the capacity utilization of the Uniformity department be increased?"*

Based upon this research, we answered the main research question. The capacity utilization of the Uniformity department can be increased by a combination of various solutions. First of all, the efficiency of the machine setup and supply process should be increased. Also, by providing training and temporarily increasing the workforce capacity utilization will increase. Furthermore, Key Performance Indicators and a proper scheduling component should be introduced. When implementing all provided solutions successfully, the performance gap will be bridged.

These conclusions are based upon various observed efficiency losses, idle time causes, and other factors influencing the capacity utilization and output. Next, we discuss the conclusions of the analyses regarding these aspects.

Both the X-ray and uniformity machines are identified as the bottleneck of the Uniformity department. Although only minor idle time is allowed for those machines, about 30% idle time is observed. During setups and the supply of tires, the machines are idle for about 11% because of 1) inefficient machine design and 2) negative operator and truck driver influence. Also during machine failure, lunch breaks, operator unavailability, and changing shifts, idle time is present.

Besides the idle time analysis, we have identified other disturbing factors. This leads to the following root causes: 1) the lack of well-defined Key Performance Indicators, 2) the lack of a proper scheduling component, 3) negative operator influence (limited amount of operators and lack of expertise), and 4) inefficient machine design regarding setups and supply. Because of these root causes, current performance is too low to deal with the incoming amount of tires. To solve the root causes, we illustrated the performance gap 2012 and provided solutions.

The existing performance gap between the current situation and the target for the coming year 2012 is about 10% capacity utilization for the uniformity machines and about 20% capacity utilization for the X-ray machines. To bridge the performance gap, we suggest implementing the following solutions:

- Reduce idle time during setups and supply by technical and organizational measures
- Provide a dynamic scheduling component, taking care of uncertainty and complexity
- Develop well-defined Key Performance Indicators to provide insight into performance
- Reduce machine failure by providing a robust solution for the conveyor belt
- Temporarily increase the amount of workforce
- Provide training by introducing ‘best practices’ to increase operator expertise

If all of the solutions above are implemented successfully, the existing performance gap will be bridged. Below, we provide more details regarding these solutions.

Improving machine setups and supply requires both technical and workforce related improvements. When adjusting machine design and developing best practices, the expected improvement potential reaches about 11%. A SMED-project seems to provide a suitable project structure. Reducing machine failure can be realized by introducing a more robust solution for the conveyor belt. It is expected that capacity utilization will be increased by about 3% within a short time period. Providing a proper scheduling component results in control regarding the ‘mix’, lead time, capacity utilization, and output. This will improve current performance. Introducing well-defined KPIs make performance visible, provide a clear goal, and direct people’s behaviour. It should be further investigated which KPIs are most suitable for the Uniformity department. By providing education and training the expertise of operators will increase, reducing idle time. This solution includes the participation of operators to construct best practices. About 7% idle time is reduced by implementing this solution. Temporary increasing the workforce shrinks idle time and increases capacity utilization. This solution quickly reduces the idle time for about 5%.

As stated earlier, when implementing all solutions successfully, the performance gap will be bridged.

6.2 FEEDBACK ON THIS RESEARCH

In this section, we reflect on dilemmas we were confronted with during the research.

During the analysis it has been argued that technical related improvement potential can be realized by introducing or adapting systems and hardware. This reduces the dependency of the workforce and increases performance. However, the workforce directly influences processes and can therefore obtain significant improvements within a relative short time period. We dealt with this issue by recommending to implement technical related improvements together with making the impact of operator behaviour visible. By providing feedback regarding the direct impact of the operator, the direct impact can be controlled.

Besides this, various solutions directly approach and solve the problem whereas other solutions do support these solutions and thereby indirectly solve the problem. We were confronted with the effect and importance of supporting solutions. Since it is hard to prove direct impact of supporting solutions, qualitative arguments become inevitable. We did this by providing insight into the causes of the lack of a supporting solution. By doing this, we were able to identify indirect causes and take them into account during the research.

6.3 RECOMMENDATIONS

In this section we provide recommendations regarding items more or less outside of the scope of this research and regarding further research.

First, it should be mentioned that the allocation of jobs to machines directly influences the required capacity utilization for the machines. Therefore, the orders, which are able to be measured on machines with low required capacity utilization, should be measured on these machine. This avoids increasing the workload for machines with an already high required capacity utilization. This implicates that all orders, which are able to be measured on uniformity machine 1 and X-ray machine 1, should be measured on these machines to avoid additional workload for uniformity machines 5 and 6.

Also, we recommend further research. First of all, we observed that in the current situation the X-ray measurement result is visually inspected by operators. This leads to the necessity to assign an operator full time to the machine. It should be further investigated whether this process can be automated, improving machine uptime and reducing operator dependency. Next, further research should be provided regarding the reduction of processing times of the uniformity machines. It is known that the processing times can be reduced by applying a different way of measuring. However, it should be investigated whether the quality and reliability of the measurement can be guaranteed. Further research can provide more insight in these issues and might lead to a reduction of processing times.

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GLOSSARY

GENERAL ABBREVIATIONS

ERP	Enterprise Resource Planning
FGI	Finished Goods Inventory
MPC	Manufacturing Planning & Control
QCS	Quality Control System
RMI	Raw Material Inventory
TPS	Toyota Production System
VSM	Value Stream Map
WIP	Work In Progress

INTERNAL ABBREVIATIONS

TSA	Temporary Storage Area

TERMINOLOGY

Capacity	maximum output that can be obtained when continuously measuring tires
Utilization	the proportion of time a machine is used
Capacity utilization	the use of capacity
Required capacity utilization	the required use of capacity to handle the amount of incoming tires
Bottleneck	the station with the highest utilization
Throughput	the average output of a production process per unit time
Cycle time	the average time from the release of a job until it reaches an inventory point
Y-tire	a tire type measured frequently during peak production periods
Peak prod. periods	periods in which a high number of tires need to be measured
Value-adding activities	activities, the (final) customer wants to pay for
Order / job	a batch of tires to be measured
Measuring machines	the X-ray and uniformity machines

APPENDICES

Appendix A: MANUFACTURING 'LAWS'

As given by Hopp & Spearman (2000, p.652-653):

- Law (Little's Law): WIP = TH x CT
- Law (Variability): "*Increasing variability always degrades the performance of a production system"* (Hopp & Spearman, 2000, p.652).
- Law (Variability Buffering): "*Variability in a production system will be buffered by some combination of 1. Inventory, 2. Capacity, and 3. Time*" (Hopp & Spearman, 2000, p.652).
- Law (Variability Placement): "*In a line where releases are independent of completions, variability early in a routing increases cycle time more than equivalent variability later in the routing*" (Hopp & Spearman, 2000, p.652).
- Law (Buffer Flexibility): "*Flexibility reduces the amount of variability buffering required in a production system"* (Hopp & Spearman, 2000, p.652).
- Law (Capacity): "*In a steady state, all plants will release work at an average rate that is strictly less than the average capacity*" (Hopp & Spearman, 2000, p.653).
- Law (Utilization): "If a station increases utilization without making any other changes, average WIP and cycle time will increase in a highly non-linear fashion" (Hopp & Spearman, 2000, p.653).
- Law (Lead Time): "The manufacturing lead time for a routing that yields a given service level is an increasing function of both the mean and standard deviation of the cycle time of the routing" (Hopp & Spearman, 2000, p.653).

Appendix B: EFFECTS OF VARIABILITY ON THE PERFORMANCE

As given by Hopp & Spearman (2000, p.331-332):

- *Variability degrades performance*. As variability increases, inventory will build up, throughput will decline, lead times will grow, and other performance-indicators decline.
- *Variability buffering is a fact of manufacturing life*. Variability is in all systems buffered using some combination of inventory, capacity and time. If capacity cannot be reduced, the following results will be inevitable: long cycle times and high inventory levels, wasted capacity, lost throughput, and long lead times.
- *Flexibility buffers are more effective than fixed buffers*. Having capacity, inventory, and time available in more than one way is more effective than being restricted in this way. Flexibility is valuable.
- *Releases are always less than capacity in the long run*. Take into account that your system is not able to operate 100% as prescribed. It is better to plan this instead of adjusting the release dates afterwards.
- *Variability early in a line is more disruptive than variability later in a line*. Variability early in the line influences all other processes whereas variability later in the line only affects its 'own' process. Therefore, a reduction in variability early in the process is the most effective way of reducing the variability of a line.
- *Cycle time increases nonlinearly in utilization*. As utilization approaches one, the WIP and cycle time approach infinity.
- *Cycle times increase proportionally with transfer batch size*. Waiting to batch and to unbatch can easily be a multiple factor of the effective processing time of a product. Reducing the batch size will improve the cycle time of the products.

Appendix C: LEAN MANUFACTURING

The aim of eliminating waste

Waste can be categorized into one of the following two types; 1) necessary activities which do not add any value but cannot be eliminated (type 1 "muda") or 2) activities which do not add any value and can (and should) be eliminated immediately (type 2 "muda") (Womack & Jones, 2007). But what exactly is waste? Waste can be best described based upon what it is *not*. Waste is the opposite of value, which can be defined only by the ultimate customer. For which activities and materials does the customer want to pay for? That, and only that, is value.

7 categories of waste

A variety of waste-categories are set up by Ohno (1988) and described by Womack & Jones (2007). The different types of waste can be categorized into seven categories: 1) Transport, 2) Inventory, 3) Movements, 4) Waiting, 5) Overproduction, 6) Over Processing, and 7) Defects. The Uniformity department will be analysed based upon these seven categories of waste. Next, the different types of waste are explained in more detail.

As given by Womack & Jones (2007):

- Transportation: transporting the goods from A to B does not add any value to the product (again: from a customer point of view). In fact, it can damage the commodity.
- Inventory: high inventory levels only involve costs and increase lead times.
- Motion: this includes the motion of people and indicates that the line is not balanced from one process to the other. Many (non-value-added) motions create a lack of overview and control.
- Waiting: goods waiting indicates again that the process is not balanced and that push mechanisms are used. Waiting does involve costs but does not add value to the product and therefore needs to be eliminated.
- Overproduction: producing too many products (strongly) indicates that a push system is used. Overproduction leads to inventory.
- Over-processing: occurs when complex solutions are applied to simple situations. Things need to be done in a right, but efficient way.
- Defects: lead to correction or re-work and does clearly not add any value to the product. Doing things right the first time, is the right (and only) way to do it.

5 Lean principles

In order to eliminate waste (and thereby adding customer value), five lean principles have been set up (Womack & Jones, 2007):

I. *Specify value:* Value can be defined only by the ultimate customer and is disordered by pre-existing organizations.

II. *Identify the value stream*: The value stream includes all processes needed to bring a product to the customer.

III. Create *flow*: Make the value-creating steps flow. Eliminate storage, waiting, and other flow-restricted aspects as much as possible.

IV. Work towards a *pull* system: Let the customer pull the product from you. *"Sell one. Make one*."

V. *Pursue perfection*: This process is an iterative process; there is no end to reducing time, space, cost, and mistakes.

To summarize, Lean is doing *more* with *less*. Using the least amount of resources while giving the customer exactly what he wants. Based upon this philosophy, the current situation at the Uniformity department is identified.

Next, we illustrate a valuable Lean tool called 'Value Stream Mapping'. This tool can help managers, operators and others users to identify efficiency losses.

Value Stream Mapping

Value Stream Map (VSM) is a Lean tool to map the flow of materials and information to identify efficiency losses. This method has been developed by Toyota as a part of the Toyota Production System (TPS). The Value Stream includes value adding and non-value adding activities required to bring a product from raw materials to the customer. Its objective is to eliminate waste, establish flow, and improve added value by identifying waste in these areas. One of the aspects of the VSM philosophy is to move from batch and push to one-piece flow and pull[30]. Lead-time, inventory, and over-production (and more types of waste) are therefore reduced; throughput, efficiency, and quality are improved (Lovelle 2001).

Creating a current state Value Map of the Uniformity department will identify current efficiency losses whereas a future state Value Map describes the situation in which those efficiency losses are eliminated.

[30] Those terms are closely related to Lean Manufacturing and are explained in the glossary

Appendix D: 5 WHY'S METHOD

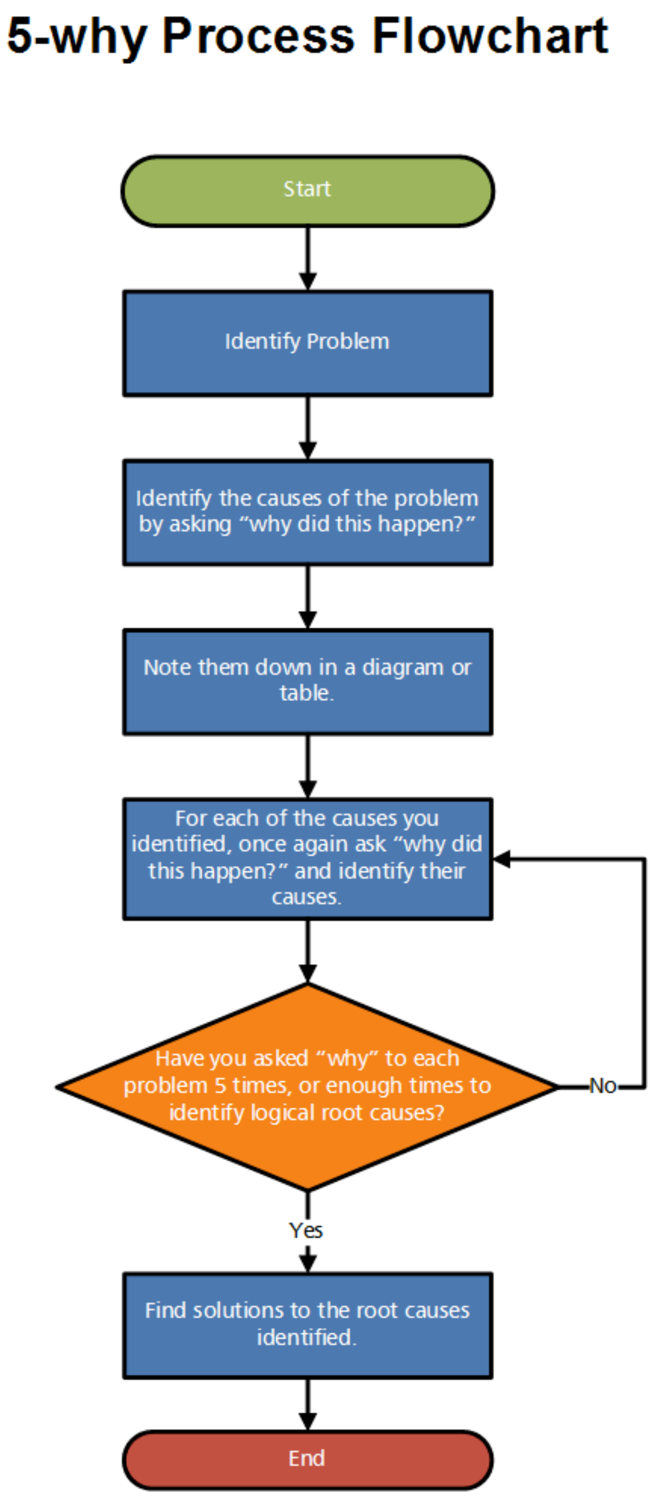

Figure 18: 5 why's process flowchart Source: Bulsuk, K.G., 2011

Appendix E: PHYSICAL FLOW OF TIRES

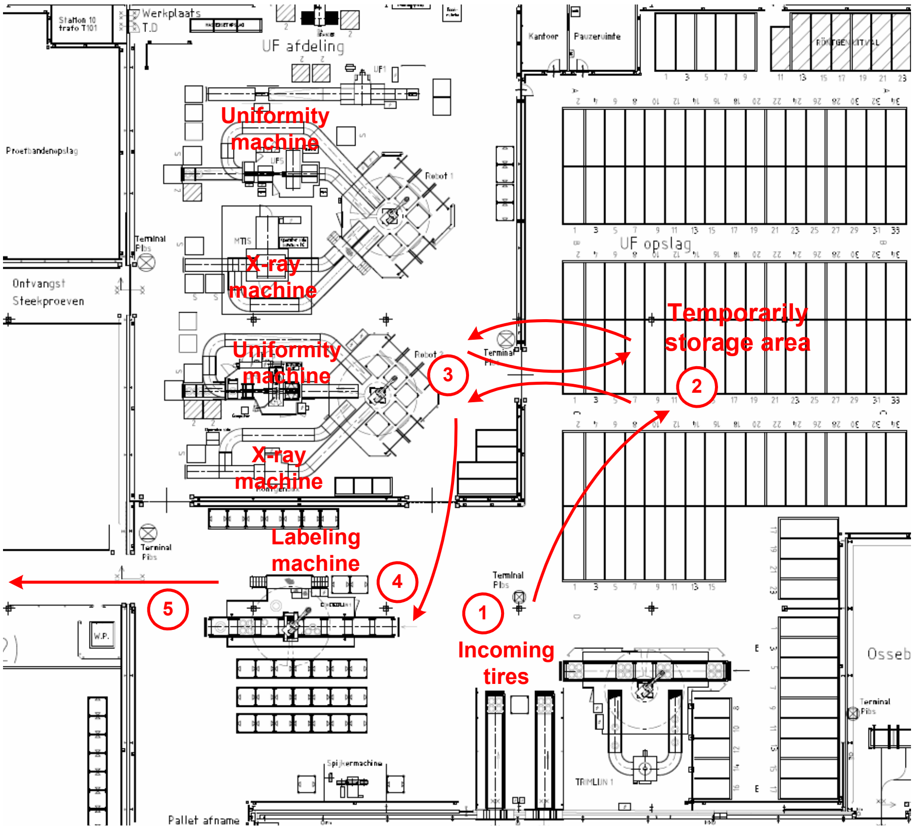

Figure 19: Physical flow of tires   Source: internal document of Apollo Vredestein B.V.

Appendix F: FLOWCHATRTS LOGISTICAL AND MEASURING ACTIVITIES

[Here we removed some content due to confidentiality reasons]

Appendix G: CLASSIFICATION OF MEASUREMENTS

[Here we removed some content due to confidentiality reasons]

Appendix H: MEASURING REGULATIONS

[Here we removed some content due to confidentiality reasons]

Appendix I: PEAK PRODUCTION CALCULATIONS

[Here we removed some content due to confidentiality reasons]

Appendix J: MAIN FLOW OF TIRES DURING PEAK PRODUCTION PERIODS

[Here we removed some content due to confidentiality reasons]

Appendix K: UTILIZATION EFFICIENCY CALCULATIONS

	X-ray		Uniformity	
Average (# tires / shift)	1050		1681	
Ideal production rate (# tires / shift)	2047	**51%**	3134	**54%**
Max production rate (# tires / shift)	1601	**66%**	2473	**68%**
Top production rate (# tires / shift)	1479	**71%**	2025	**83%**

Table 10: overview of utilization efficiency based upon a variety of definitions (based upon ERP-system data)

Appendix L: OPERATOR MOVEMENTS

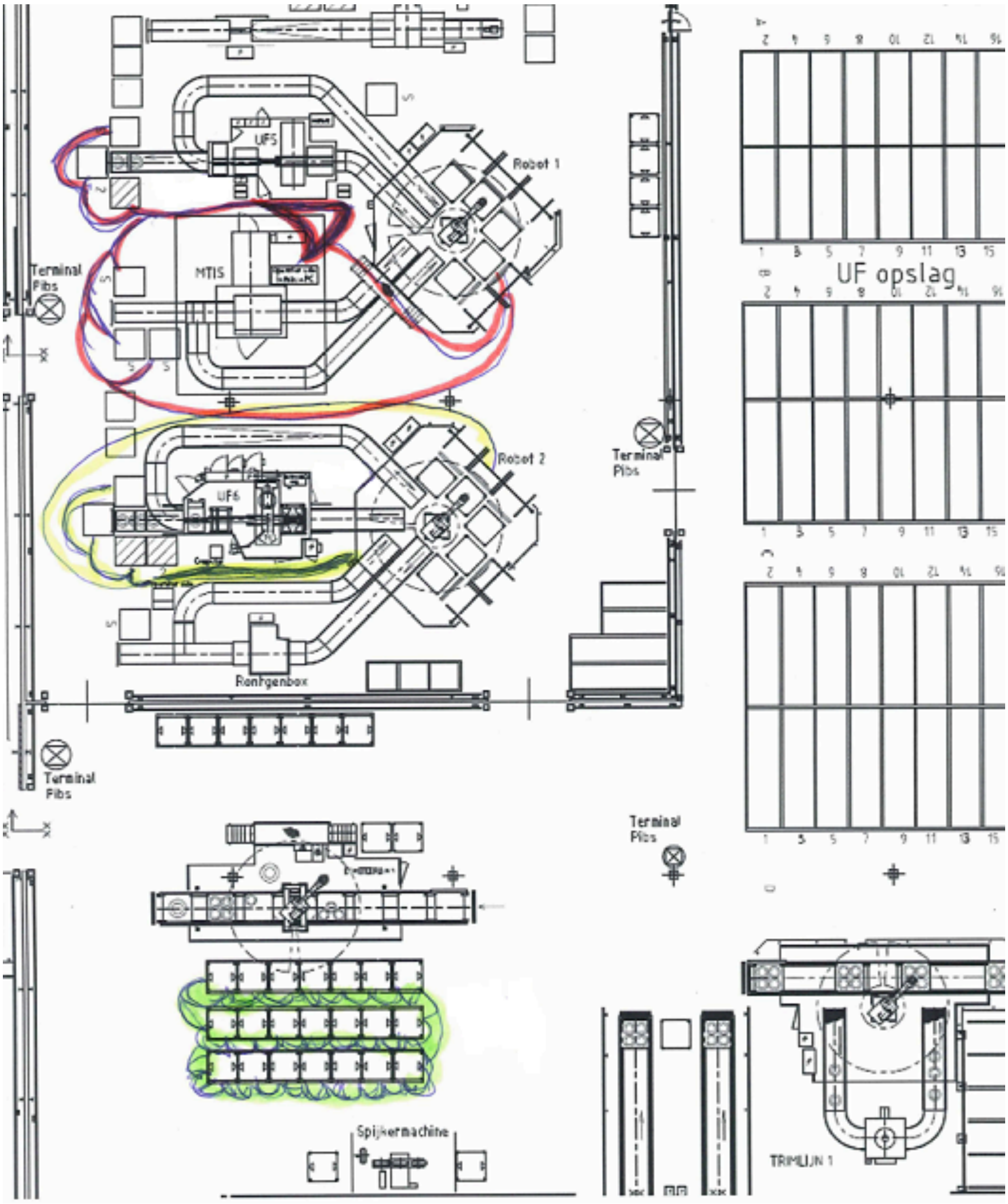

Figure 20: a layout diagram including operator movements

Appendix M: EXAMPLE OF ORDER SCHEDULE

PP839 PLANNING UNIFORMITY Datum 12/04/11
Datum: 12/04/11 Dienst: 2 15:05

Nr	Aktikelkode	Mt	Tst	Ord	*-Aantal-* Test	Voorr	Prod min	Wis min	*---Gepland---* Datum	Tijd	
1	**** START ****	15							12/04	13:36	UF1
6	T185/60R14TTS	14	235	39588	14	330	27	15	12/04	16:52	UF1
7	T165/70R14ZV	14	271	39587	14	330	27	1	12/04	17:20	UF1
8	T165/70R14SN3	14	507	39586	32	330	62	1	12/04	18:23	UF1
	Totaal				60						
9	**** START ****								12/04	13:37	UF5
10	Y215/40R16ULCX	16	797	39150	525	525		1	12/04	12:31	UF5
11	V205/55R16QT3X	16	396	39510	10	10	23	1	12/04	12:55	UF5
16	Y225/55R16ULC	16	479	39357	156	400	364	1	12/04	23:48	UF5
17	Y205/60R16ULCX	16	796	39434	594	594	1385	1	13/04	22:54	UF5
18	Y205/55R16ULC	16	471	39550	682	682	1590	1	15/04	1:25	UF5
19	H235/60R16Q3S	16	665	39284	1080	1080	2517	1	16/04	19:23	UF5
20	H235/65R17Q3SX	17	666	39456	570	570	1329	15	17/04	17:47	UF5
21	V235/65R17U4SX	17	630	39447	540	540	1259	1	18/04	14:47	UF5
22	Y205/50R17ULCX	17	539	39356	460	460	1072	1	19/04	8:40	UF5

Figure 21: example of the order schedule of the uniformity machines Source: internal document of Apollo Vredestein B.V.

PP845 PLANNING RONTGEN Datum 12/04/11
Datum: 12/04/11 Dienst: 2 15:09

Nr	Aktikelkode	Mt	Tst	Ord	*-Aantal-* Test	Voorr	Prod min	Wis min	*---Gepland---* Datum	Tijd	
1	**** START ****	15							12/04	13:34	R01
2	Y215/40R16ULCX	16	797	39150	125	125 U	192	1	12/04	15:43	R01
3	H185/60R15QT3X	15	374	39579	14	312	22	1	12/04	16:06	R01
	Totaal				139						
6	**** START ****	17							12/04	12:30	R02
7	Y305/35R22U4SX	22	581	39270	417	417	803	1	13/04	1:54	R02
DEJONGH	855	*** PRINTEN PLANNING UF ***								12/04/	
8	Y265/30R22ULSX	22	570	39509	368	368	709	1	13/04	13:44	R02
9	Y295/30R22U4SX	22	579	39437	430	430	829	1	14/04	3:34	R02
10	Y225/45R18ULSX	18	713	39562	236	236	455	1	14/04	11:10	R02
11	W255/55R18U4SX	18	789	39539	247	247	476	1	14/04	19:07	R02
12	Y215/40R18ULCX	18	531	39551	286	286	551	1	15/04	4:19	R02
13	Y245/45R18ULSX	18	726	39540	286	286	551	1	15/04	13:31	R02

Figure 22: example of the order schedule of the X-ray machines Source: internal document of Apollo Vredestein B.V.

Appendix N: DATA COLLECTION FORM

[Here we removed some content due to confidentiality reasons]

Appendix O: IDLE TIME (SUB)CATEGORIES

We split up the idle time into preemptive and *non*-preemptive outages[31]. We make this distinction since both outages ask for a different approach. Preemptive outages require immediate action whereas non-preemptive outages can be planned on beforehand. In order to be able to allocate the observed idle time, we set up some idle time categories (see Table 2). Furthermore, two additional categories are added to provide a comprehensive allocation of observed idle time into categories: 1) a category called ‘unavailability’ indicating whether an operator is (or is not) present at the machine when required (excluding breaks) and 2) a category ‘expertise’ indicating the (lack of) expertise of an operator.

Next, we discuss the categories within the type of non-preemptive outages. The changeover activities relate to the exchange of flanges due to the different tire types, differing in diameter size. This task is only necessary for Uniformity machine 6 since this machine only uses flanges consisting of a single diameter size for each flange. Uniformity machine 5 has an advanced flange, consisting of three different diameter sizes resulting in changeover activities occurring only incidentally. Furthermore, setups are performed when switching to a new order due to different tire and measurement specifications. This idle time category is split up in the tasks needed to prepare the machine for the new order and the influence of both the operator and the truck driver during this process. This is excluding the changeover activities, since in most cases the machine is set up for a new order without the need for a changeover. Next, the category ‘swapping pallets’ is added to indicate the transportation of pallets from and to the measuring machines. Also the category ‘breaks’ is taken into account. This category includes coffee and/or lunch breaks. Finally, the category ‘changing shifts’ is used to allocate the amount of idle time occurring between changing the shifts (morning-shift / afternoon-shift / night-shift).

[31] Preemptive outages are disturbances that can occur at every sudden moment. *Non*preemptive outages are stoppages that occur between, rather than during, jobs (Hopp & Spearman, 2000).

Appendix P: CHI-SQUARE TEST RESULTS

Category	Subcategories	Chi-square value		Probability (%/100)	
		UF 5	UF 6	UF 5	UF 6
Machine failure	Robot machine failure	5.99	6.56	0.54	0.48
	Conveyor belt failure	8.38	n.a.	0.30	n.a.
	Measuring machine failure	2.45	n.a.	0.93	n.a.
Changeover activities	Changeover tasks	n.a.	n.a.	n.a.	n.a.
	Influence operator	n.a.	n.a.	n.a.	n.a.
Setups	Conveyor belt and other setup tasks	3.11	2.66	0.87	0.91
	Influence operator	3.07	1.19	0.88	0.99
	Influence truck driver	6.32	1.19	0.50	0.99
Swapping pallets	Influence truck driver	3.73	2.25	0.81	0.94
Breaks	Influence operator	1.66	4.33	0.98	0.74
Changing shifts	Influence operator	1.32	2.34	0.99	0.94
Unavailability	Influence operator	3.08	2.71	0.88	0.91
Lack of expertise	Influence operator	3.00	3.01	0.89	0.88
Total	Average	**3.83**	**2.92**	**0.80**	**0.89**

Table 11: chi-square results of idle time subcategories

The underlined chi-square values correspond to the subcategories which are less significant compared to the remaining subcategories. First of all, both uniformity machines show a low chi-square value regarding the robot machine failure. This can be explained by the observation that the occurrence of robot machine failure depends largely on the operator, caused by adjusting the instrument panel settings of the machine with wrong settings. This results in observations in which the robot machine often fails and observations in which the robot machine works very well. This difference in observation results in a relative low chi-square value and implicates that this observation of idle time cannot be generalized among all cases.

Besides that, the results show a relative low chi-square value for uniformity machine 5 regarding the conveyor belt failure. The low significance of the conveyor belt failure has to do with the observation that this failure often is caused by a specific tire type. This results in the observation that at some time periods, the conveyor belt often fails and that during some time periods, the conveyor belt works fine. This difference in observation results in a relative low chi-square value and implicates that this observation of idle time cannot be generalized among all cases. Finally, the significance regarding the influence of the truck driver during setups turns out to be low. This has to do with the lack of truck driver expertise and does therefore occur in an irregular way.

Appendix Q: X-RAY vs. UF process

Both observations and time studies, as performed by the Organization department, show that the main tasks at both machines are almost the same. The only major difference is that the tires at the X-ray machines need to be visually checked.

	Uniformity machine	X-ray machine
1. Add new orders at the machine instrument panel	YES / ~~NO~~	YES / ~~NO~~
2. Close current order at robot	YES / ~~NO~~	YES / ~~NO~~
3. Add new order at robot instrument panel	YES / ~~NO~~	YES / ~~NO~~
(4. Visually check each tire)	~~YES~~ / NO	YES / ~~NO~~

Table 12: main tasks at both the Uniformity and X-ray machines

Appendix R: FACTORS INFLUENCING THE CAPACITY UTILIZATION AND OUTPUT

[Here we removed some content due to confidentiality reasons]

Figure 23: Overview of factors influencing the capacity utilization and output

Next section provides a global description of the elements, shown in Figure 23. This can be useful for readers with less background information.

Organization

Taking into account the organizational aspect, we observe three parties involved mainly influencing the aspects regarding the workforce. First of all, the production manager is responsible for the whole production line. He gives orders to the coordinator of the Uniformity department, responsible for coordinating the activities at this department. Next, a coordinator sets up a workforce schedule. However, an employee of the department of Organization determines the workforce planning. This includes the amount of required operators. As one might imagine, this workforce planning significantly influences the scheduling possibilities.

Workforce

Based upon the workforce schedule, the operators are assigned to a specific task. The main tasks influencing the capacity utilization of the Uniformity department most are supplying and operating the machines. Since the amount of operators available to be assigned is limited, the number of operators to be assigned to the X-ray machine interacts with the operators to be assigned to the uniformity machine. As we elaborate more on later, the amount and expertise of machine operators significantly influences the capacity utilization of both measurement machines.

Transport

The idle time analysis already clarifies that the transport of tires to supply the measurement machines, directly influences the capacity utilization. Furthermore, we observed that the number of truck drivers and the truck driver expertise also directly influence the capacity utilization. During several scenarios[32], it is known that the truck driver supplying the measurement machines is pressed for time. One of the influencing factors arises from the tire type to be transported, as we will elaborate on when discussing the 'tire aspects'. Also a lack of space during peak production periods makes transportation of tires even more difficult.

[32] For example when only a few tires fit on a pallet more transport activities need to be performed.

Measurements

The main value-adding process at the Uniformity department is performing measurements. As already mentioned, the capacity utilization of both measurement machines is influenced by the operator, the truck driver, setups, and the amount of re-tests. Next to these factors, the tire type plays an important role too.

Tire aspects

Many observations can be mentioned regarding the tire aspects, since it influences a variety of elements. The tire type influences the supply mainly by the number of tires on the pallet. When less tires of a specific tire type fit on a pallet, the truck driver needs to perform more transport activities to avoid that the machine is getting idle.

[Here we removed some content due to confidentiality reasons]

Labelling

The amount of tires measured and the amount of tires not measured are all labelled. This results in the output of the Uniformity department.

Order Scheduling

Based upon the inventory level, available orders are provided. Next, the coordinator makes a selection, based upon personal insight, resulting in a schedule. The selection of orders impacts both the lead time of the tires and the 'mix' of tires.

[Here we removed some content due to confidentiality reasons]

Output

All the above mentioned factors directly or indirectly influence the output of the Uniformity department. With the output, we mean the total number of tires transported from the Uniformity department to the warehouse for finished goods.

Appendix S: FIGURES ILLUSTRATING HIGH VARIANCE

[Here we removed some content due to confidentiality reasons]

Appendix T: OVERVIEW OF PERFORMANCE GAP AND IMPROVEMENT POTENTIAL CALCULATIONS

UF 5		
Design:		
Setups	4%	
Pallet swaps	6%	
Solved by design	10%	
Reducing machine	2%	1%
failures	3%	2%
Technical related		**13%**
Training:		
Setups	4%	2%
Pallet swaps	2%	1%
Unavailability	4%	2%
Breaks	4%	2%
Expertise	4%	2%
Changing shifts	3%	2%
Workforce related		**10%**
Overall potential		**23%**
Current Utilization		63%
Required Utilization		74%
Performance gap		**11%**

UF 6		
Design:		
Setups	1%	
Pallet swaps	6%	
Solved by design	7%	
Reducing machine failures	3%	2%
Technical related		**9%**
Training:		
Setups	3%	2%
Pallet swaps	2%	1%
Availability	4%	2%
Breaks	6%	3%
Expertise	5%	3%
Changing shifts	1%	1%
Workforce related		**10%**
Overall potential		**19%**
Current Utilization		68%
Required Utilization		80%
Performance gap		**12%**

X-ray 1		
Design:		
Setups	2%	
Pallet swaps	5%	
Solved by design	7%	
Reducing machine failures	3%	2%
Technical related		**9%**
Training:		
Setups	2%	1%
Pallet swaps	1%	1%
Availability	8%	6%
Breaks	5%	3%
Expertise	4%	2%
Changing shifts	3%	2%
Workforce related		**13%**
Overall potential		**22%**
Current Utilization		68%
Required Utilization		89%
Performance gap		**21%**

X-ray 2		
Design:		
Setups	3%	
Pallet swaps	5%	
Solved by design	8%	
Reducing machine failures	3%	2%
Technical related		**10%**
Training:		
Setups	2%	1%
Pallet swaps	1%	1%
Availability	8%	6%
Breaks	5%	3%
Expertise	4%	2%
Changing shifts	3%	2%
Workforce related		**13%**
Overall potential		**23%**
Current Utilization		69%
Required Utilization		88%
Performance gap		**19%**

Table 13: performance gap and improvement potential calculations

Appendix U: BRAINSTORM SESSION OUTCOME

See below for the outcome of the brainstorm session. An initial selection of ideas is performed by judging them on 'complexity' and 'effectiveness'. This results in the following overview:

SETUP

1. **Better preparation**
2. **A single receipt for UF & robot**
3. **Communication operator – trucker**
4. **Improve knowledge / expertise**
5. **Buffering for continuous supply**
6. **Auto-supply instead of truck driver**
7. **Introduce better KPIs**
8. **Increase robot-'intelligence'**
9. **Introduce S.M.E.D. project**
10. **Improve current planning**
11. ~~Central control for operators~~
12. ~~Simcorp-systeem for supply~~
13. ~~'Track & Trace'~~
14. ~~Eliminate setups~~
15. ~~Robot determines receipt~~
16. ~~Universal receipt~~
17. ~~Simplify positioning pallet~~

MACHINE FAILURE

1. **Increase maintenance (PIPO)**
2. **Better cleaning**
3. **Improve education operator**
4. **Good 'spare-part' policy**
5. **Use M.A.R.S.**
6. ~~Reduce 'flash'~~
7. ~~Check machine when switching shifts~~
8. ~~'Remote access'~~

(LUNCH) BREAKS

1. **Communication truck driver and operator**
2. **Alarm when machine gets idle**
3. **Temporary substitute during breaks**
4. **Increase buffer size**
5. ~~Breaks at workstation~~
6. ~~Breaks during machine failure~~

EXPERTISE

1. **Keeping employees**
2. **Increase education**
3. ~~Improve 'Randstadters'~~
4. ~~Eliminate language barrier~~

UNAVAILABILITY

1. **Determine well 'mix'**
2. **Higher educated employees**
3. **Prioritise machines**
4. **Enough workforce**
5. **Better KPIs**
6. ~~All machines require an operator~~
7. ~~Incentives for less idle time~~

SWAPPING PALLETS (SUPPLY)

1. **Improve planning**
2. ~~Improve quality of pallets~~
3. ~~Direct supply from vulcanisation~~
4. ~~Alternative way of transporting the tires~~

CHANGING SHIFTS

1. **Revise preparation**
2. **Earlier arrival**
3. **Clear transfer of changing shifts**
4. **Counting tires by coordinator**
5. **Introduce clear KPIs**

Appendix V: REQUIREMENTS FOR SETTING UP CRITERIA

As given by Keeney and Raiffa (2003).

The overview of criteria needs to be:

- Complete, all relevant criteria should be included
- Non-redundant, eliminate redundant or overlapping criteria
- Operational, criteria should be measurable
- Independent, criteria need to be independent from each other
- Limited amount, total amount of criteria should not be larger than necessary

Appendix W: SENSITIVITY ANALYSIS CALCULATIONS

Origin weights, scores, and rankings

40	3	1	3	3	2	1
15	2	2	2	3	2	3
15	3	4	2	2	1	4
30	2	3	2	3	2	4
100	255	220	240	285	185	265
	3	**5**	**4**	**1**	**6**	**2**

Improvement potential

30	3	1	3	3	2	1
15	2	2	2	3	2	3
15	3	4	2	2	1	4
30	2	3	2	3	2	4
	225	210	210	255	165	255
	3	**5**	**4**	**1**	**6**	**2**

50	3	1	3	3	2	1
15	2	2	2	3	2	3
15	3	4	2	2	1	4
30	2	3	2	3	2	4
	285	230	270	315	205	275
	2	**5**	**4**	**1**	**6**	**3**

Implementation time

40	3	1	3	3	2	1
15	2	2	2	3	2	3
15	3	4	2	2	1	4
20	2	3	2	3	2	4
	235	190	220	255	165	225
	2	**5**	**4**	**1**	**6**	**3**

40	3	1	3	3	2	1
15	2	2	2	3	2	3
15	3	4	2	2	1	4
40	2	3	2	3	2	4
	275	250	260	315	205	305
	3	**5**	**4**	**1**	**6**	**2**

Costs

40	3	1	3	3	2	1
5	2	2	2	3	2	3
15	3	4	2	2	1	4
30	2	3	2	3	2	4
	235	200	220	255	165	235
	3	**5**	**4**	**1**	**6**	**2**

40	3	1	3	3	2	1
25	2	2	2	3	2	3
15	3	4	2	2	1	4
30	2	3	2	3	2	4
	275	240	260	315	205	295
	3	**5**	**4**	**1**	**6**	**2**

Ease of acceptation

40	3	1	3	3	2	1
15	2	2	2	3	2	3
5	3	4	2	2	1	4
30	2	3	2	3	2	4
	225	180	220	265	175	225
	3	**5**	**4**	**1**	**6**	**2**

40	3	1	3	3	2	1
15	2	2	2	3	2	3
25	3	4	2	2	1	4
30	2	3	2	3	2	4
	285	260	260	305	195	305
	3	**5**	**4**	**1**	**6**	**2**