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Tube mill optimization at Tata Steel Tubes

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Tube mill optimization at Tata Steel Tubes under the supervision of The University of Twente

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Preface

September 2015, I attended the Kick-In introduction week at the University of Twente as a freshman. Now, at the end of my third academic year, I am writing this preface. I realise that I have almost finished my bachelor's degree, which is amazing. I remember the orientation day of Industrial Engineering and the lecturer was talking about the graduation at the end of the bachelors. It seemed so far away. In my third academic year, I went to Jyväskylä (Finland) to study abroad at the Jyväskylän ylipisto. I followed some totally un-IEM-related courses in Finland; politics and communication. It was a great adventure and a change of perspective. I am looking forward to the future.

First, I would like to thank Sanne Kramer, who was my supervisor at Tata Steel tubes. You gave me a lot of freedom and space to create my own 'project', but provided guidance when necessary. Also, I really liked our talks about people management, organizational issues and strategic planning with all the practical examples from the Tata Steel organization.

Second, I would like to thank Jos van Hillegersberg, who was my first supervisor at the University of Twente. I would like to thank you for your time, your guidance and support. We discussed many research related topic and you advised me on all the issues I encountered during the project.

Third, I would like to thank Marco Schutten. Thank you for making time to be the second supervisor of my thesis.

I wish Sanne, Jos and Marco all the best in the upcoming future in both their personal and professional lives.

Kevin Roy Commandeur, July 2018

Management summary

The aim of the research was to alter the processing speed of the bottleneck in the M-93 (tube mill at Tata Steel Tubes). Increasing the processing speed of the bottleneck implies that the speed at which the tubes arrive in the outside storage increases and since the demand of the tubes in the research scope is higher than the supply, an increased speed implies an increased turnover and profit. The goal was set to increasing the bottleneck's processing speed up to the speed of the tube mill, since the bottleneck is stalling the tube mill massively. The research scope was set to the tubes that are bundled with 2 tubes in one bundle, which are the 323 and 273 (tube diameter). These numbers will be used to refer to the tubes with the corresponding diameter.

We conducted literature research to set up a theoretical framework to support the reasoning and decisions in the field research. The topic of the theoretical framework is the Theory of Constraints (TOC). In the field research, several TOC tools, TOC methodology, TOC definitions and TOC logic is used to form arguments and describe phenomena. The first step in the field research was to identify the constraining process of the production line. This turned out to be the bundling process. We distinguish two processes in the bundling process:

1. Forming the desired bundle shape: how many tubes per bundle and how are they stacked upon each other?
2. Strapping the bundle.

The second step turned out to be the bottleneck. We took time samples from the strapping process and set up a timeline of the process. Additionally, we analysed the strapping process with the use of a Current Reality Tree (CRT). The combination of the timeline and the CRT provided a clear picture of the current situation and has set the direction of the solution generation phase. The process downstream of the strapping process, which is the placement of the previously strapped bundle in the draining queue, turned out to be stalling the strapping process. This is the most prominent constraining factor of the strapping process. Reducing the processing time of placing the previously strapped bundle in the draining queue will decrease the time that the strapping process is hindered. Furthermore, with the use of 3 Evaporation Clouds (a TOC tool), 3 additional improvement possibilities have been identified:

1. Invest in an additional strapping machine to increase capacity
2. Strap with a stronger strapping material to reduce the number of straps needed from 6 to 4.
3. Increase the number of tubes in one bundle from 2 to 5 tubes.

We determined the effectiveness of reducing the processing time of placing the previously strapped bundle and the 3 additional improvement possibilities with the use of a simulation study. A decrease in processing time of 25% of placing the previously strapped bundle in the draining queue, would increase the strapping speed with approximately 17%. Furthermore, combining this intervention with an extra strapping machine or stronger strapping material increases the strapping speed with approximately 40%. Finally, increasing the tubes per bundle from 2 tubes to 5 tubes will increase the strapping speed to 70.6 meter per minute, however this intervention can only be implemented for the 323 and 273 with a wall thickness up to 5 mm and only a part of the customers can process bundles of 5 tubes.

Based on the research we recommend taking the following steps:

1. Identify customers that can process bundles of 5 tubes for the 323 and 273 with a wall thickness up to 5 mm. Supply those customers, the bundles consisting of 5 tubes.
2. Discuss the possibility of bundles consisting of 5 tubes with the customers that claim that they cannot process them. Evaluate their assumptions and reasoning.

3. Decrease the time that the strapping process is hindered by placing the previously strapped bundle in the draining queue.
4. Switch from the 31.75x0.8 MK strapping material to the 31.75x0.8 HT strapping material, which has a higher break force. This will result in a reduced strapping time and reduces the number of straps needed to strap one bundle. Further research is required to determine the effect of the increased strap strength on the tubes outside of this research scope.

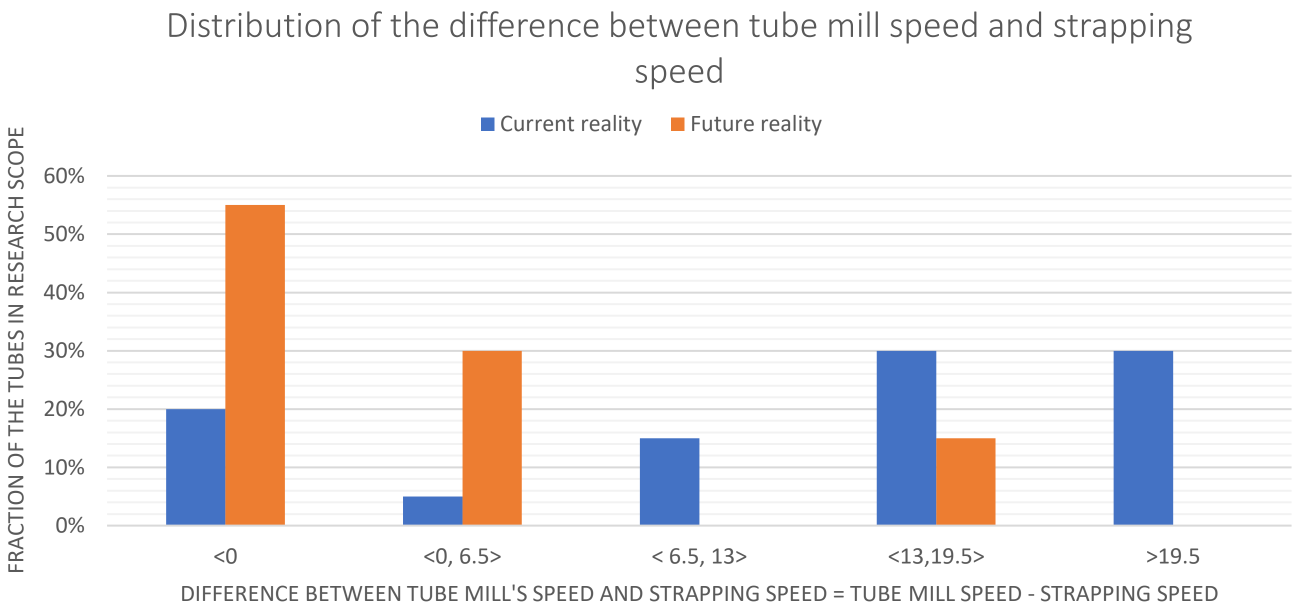


Figure 1: Distribution of the difference between the tube mill speed and strapping speed

The goal has been met for a part of the tubes in the research scope. After the recommended interventions for 55% of the tubes in the research scope, the strapping speed is higher than the tube mill's speed and for 85% of the tubes the difference between tube mill speed and strapping speed is only 6.5 meter per minute or lower. Figure 1 shows the distribution of the difference between tube mill speed and strapping speed in the current reality and future reality. Future reality refers to the scenario after the recommended interventions have been implemented. The centre of mass in the current reality is mostly focussed on the right side of the graph, which implies a big difference between tube mill speed and strapping speed. In the future reality, the centre of mass has moved to the left side, which implies a very low difference or non-existing difference between the tube mill speed and strapping speed.

Contents

1 Definitions

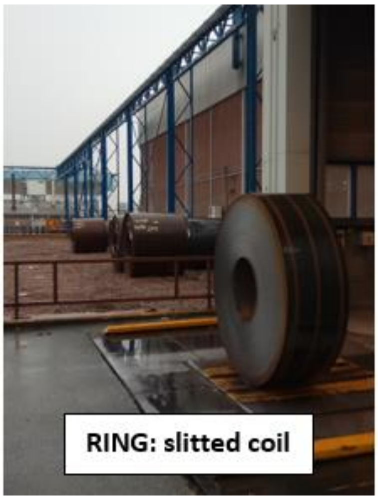
General definitions

- **TOC:** Theory of constraints
- **KPI:** Key performance indictor
- **WIP:** Work in progress
- **Chain:** The chain of processes
- **Workstation:** One of the processes in the chain
- **Tube profile:** The shape of the tube, which can be round, rectangular or squared.
- **ROI:** Return on investment
- **Net profit:** Profit minus all operating expenses
- **Cash flow:** Cash and cash-equivalents moving into and out of a business
- **Downstream:** All the workstations after the workstation in question
- **Upstream:** All the workstations before the workstation in question
- **Plant Simulation:** The software program that is used to simulate the M-93
- **Processing time:** The time it takes for a workstation to produce 1 product
- **OEE:** Overall equipment effectiveness, which is determined by quality, speed and availability.
- **In-line measurement data**: measurements taken in the tube mill while producing tubes.

TOC definitions

- **The system:** The whole chain of processes that start when an order is received and ends when the order has been paid for.
- **The bottleneck:** the process which capacity equals or is below the demand (Goldratt, 1999)
- **Throughput rate:** The rate at which the system generates money through sales (Naor & Coman, 2013), (Tulasi & Rao, 2012)
- **Inventory**: All the money that the system invests in purchasing things it intends to sell (Naor & Coman, 2013), (Tulasi & Rao, 2012)
- **Operations expenses:** All the money the system spends to turn inventory into money (Naor & Coman, 2013), (Tulasi & Rao, 2012)
- **DBR:** Drum-Buffer-Rope concept
- **Thinking Processes (TP):** Logic diagrams that are used identify the constraint and increase its performance
- **Current Reality Tree (CRT):** One of the TP tools, for more info see the section on TP
- **Evaporating Cloud (EC):** One of the TP tools, for more info see the section on TP
- **Future Reality Tree (FRT):** One of the TP tools, for more info see the section on TP
- **Prerequisite Tree (PT):** One of the TP tools, for more info see the section on TP
- **Transition Tree (TP):** One of the TP tools, for more info see the section on TP
- **UDEs:** Undesired effects
- **Injection:** action that will solve the problem; a solution

Process definitions



2 Introduction

2.1 Intro to Tata Steel Tubes

Tata Steel Tubes is a subsidiary of Tata Steel Europe. Tata Steel Tubes has 3 sites in the Netherlands: one in Zwijndrecht, one in Oosterhout and one in Maastricht. All these sites are located near rivers to ensure a constant supply of steel from Tata Steel IJmuiden. This research has been conducted at the production site in Zwijndrecht and focussed on the tube mill called the M-93. The tubes produced at the M-93 are used in the construction industry. In this report M-93 refers to the whole chain of processes from tube mill to the outside storage.

2.2 The problem

The speed at which the 323 and 273 (tube diameter in mm) arrive in the outside storage is too low. Currently, the processing speed of the tube mill is far higher than the speed at which the tubes arrive in the storage. This indicates that the output speed is constrained by one of the processes between the tube mill and the outside storage. This constraining factor leads to the tube mill being stalled, which implies that the tube mill's capacity is lost. The goal of this graduation project is to find an interventention that can alter the processing speed of the bottleneck up to the processing speed of the tube mill. The exact bottleneck still has to be pinpointed. Furthermore, the demand of the 323 and 273 is bigger than the current supply, so an increase in output speed implies an increase in sales. The processing speed of the tube mill differs depending on the wall thickness, diameter and length of the tube. The research scope consists of the 273 and 323. The total product range, concerning wall thickness is included and the tube length equals 12 meters. The tube length has been set to 12 meters, because that is the most common tube length that is produced. Appendix A shows the processing speed of the tube mill when producing the tubes in the research scope (norm values).

2.3 The problem-solving approach

First, we conducted a literature review on production process optimization theory. Second, we performed an in-depth analysis of the production line to find the cause for the underperformance on the output speed. The research variable 'processing speed per workstation' in combination with a current reality tree were used to find the cause. We found appropriate solutions after implementing the evaporation cloud and future reality tree (Theory of Constraints). Finally, we determined the effectiveness of the solutions with the use of a simulation study.

2.4 Research

The research is guided by the following questions:

(1) What is the cause of the underperformance on the speed at which the tubes arrive in the outside storage of the M-93 at Tata Steel Tubes?
Goal: To identify the bottleneck and to understand the cause of the problem, such that the proposed interventions address the problem accurately.

(2) What interventions can eliminate the cause of the underperformance on the speed at which the tubes arrive in the outside storage of the M-93 at Tata Steel Tubes?
Goal: To find effective solutions to the problem.

- Sub1-RQ1: What is the processing speed of the tube mill, bundling process, draining process and transportation process to the outside storage in meters of tube per minute?
Goal: To find the bottleneck workstation, after which it can be analysed in detail to find the root cause.
- Sub2-RQ2: How to apply the Theory of Constraints to (1) identify the constraint and (2) increase the constraint's capacity?
Goal: To create a theoretical framework on which the reasoning and made decisions can be based.

The sub-research questions were used to answer the main questions 1 and 2.

2.5 Report outline

After the introduction, the theoretical framework is presented. The theoretical framework describes the Theory of Constraints. The TOC is used as a baseline for the problem-solving approach and to support the decision-making. Second, the research that has been conducted to answer RQ1 is described. Third, we deep-dive into the constraining workstation and identify various improvement possibilities. The last part evaluates each of the possible interventions regarding output speed increase with the use of a simulation model.

3 Theoretical framework

The theoretical framework answers the question: How to apply TOC to (1) identify the constraint and (2) increase the constraint's capacity? Before TOC has been chosen as a theoretical framework, a preliminary literature review has been conducted on different process optimization theories. This preliminary research will be explained in 2.1. The main part (starting from 2.2) consists of two parts. The first part consists of an introduction on TOC. It's problem solving methodology, TOC measurement, the reasoning behind TOC and the Drum-Buffer-Rope principle (DBR) will be explained. The second part will go into the application of TOC, so the thinking processes (TOC tools) and the application of DBR are described.

Note: Some of the terms used below are defined differently compared to their definition in other scientific literature. The definitions can be found in 1. definitions – 'TOC definitions'.

3.1 Optimal process optimization methodology

We compared the Theory of Constraints (TOC), Lean and Six Sigma to find the best fitting process optimization methodology to address the problem at Tata Steel Tubes. This paragraph describes the differences between the three. The focus of the three methodologies differ. TOC focusses on the bottleneck in the chain to increase the chain's throughput, Lean focusses on the reduction of waste in the whole chain and Six Sigma focusses on the reduction of variance (Nave, 2002). The effect of a reduced variance in the chain because of Six Sigma is a more uniform and reliable output. The reduced waste (Lean) leads to decreased costs and reduced flow time. The Six Sigma approach relies heavily on measurement, data and statistical analysis. Unfortunately, Tata Steel Tubes does not have the measures to perform such an advanced analysis concerning the problem at hand. The big difference between TOC and Lean is that Lean has a 'whole chain' approach and TOC takes a 'bottleneck' approach (Dettmer, 2008). Since, reduced waste is the desired effect of Lean, it is best to analyse the whole chain and remove all the identified waste. The purpose will be achieved. However, this is not the best way to increase the throughput. The throughput is determined by the processing speed of the bottleneck, thus reducing waste in non-bottleneck processes will not increase the throughput. In the first phase of TOC, the bottleneck is identified and the next four steps focusses explicitly on the bottleneck. The methodologies have secondary effects, for example the reduced variance (Six Sigma) will increase throughput and the reduced waste (Lean) will decrease flow time and increase throughput, but the methodologies have the biggest impact on their primary focus. The focus of the study is to increase the output speed of the whole chain. Currently, the output speed is lower than the tube mill's speed. This implies that the output speed is constrained by one of the processes between the tube mill and the outside storage. The focus of the study should be in line with the focus of the optimization methodology. TOC meets this criterium most accurately.

Some scholars criticize TOC. They argue that the TOC results are feasible, but not optimal (Watson, Blackstone, Gardiner, 2006). However, Mabin (2003) conducted a study on the success of TOC. She conducted a meta-analysis of 80 TOC applications. All the TOC applications showed significant improvements in both operational and financial performance. Despite, extensive searches, the research found no reports of failures (Mabin, 2003). Noar, Bernardes and Coman (2012) evaluated the Theory of Constraints on whether it is a valid theory of not. They used Wacker's framework for theory building for the evaluation. Wacker's framework was used, because it reflects apparent consensus among philosophers of science concerning the definitional components of a theory and the common set of virtues of a good theory. The analysis pointed out that TOC is a good theory and that TOC is a meaningful body of knowledge to the OM community (Noar, Bernades, Coman, 2012). Mahesh, Gupta and Lynn (2008) argue that TOC provides approaches to operation decision that avoid pitfalls of local optimization and that TOC can serve as a unifying theory for operations management.

3.2 The TOC methodology

Eliyahu M. Goldratt is the originator of the Theory of Constraints (Goldratt, 2004). The TOC philosophy focusses on continuous improvement of a certain system. The theory has been applied by many companies with tremendous success (Mabin, 2003). A major component of TOC that underpins all the other parts of the methodology is the TOC Thinking Processes. They address the 3-fundamental questions of (1) What to change? (2) What to change it into? (3) How to cause the change? They guide the user of the TOC methodology through the decision-making process of the problem structuring, problem identification, solution building, identification of barriers to be overcome and implementation of the solution.

TOC views the system as a chain and each process in the chain as a link. All the links need to work together to achieve the goal of the chain. In the TOC literature the chain is called '*The system'*. It is assumed that there always is 1 constraining factor that limits the performance level of the chain. The theory of constraints does not view this constraining factor in a negative way, but to the contrary in a positive way. The constraining factor is the key to optimization. If the constraining factor is identified, it can be acted upon or the other operations can be set to operate with it. The TOC methodology follows the following steps:

(1) Identify the constraint in the system.
(2) Exploit the constraint. Exploiting the constraint implies that the constraint performs at its 100% capacity.
(3) Subordinate the other processes in the system to the constraint. The performance of the other processes should meet the performance of the constraint to prevent excessive inventory and high operation expenses.
(4) Elevate the performance of the constraint and by doing so, elevate the performance of the system.
(5) Repeat the process

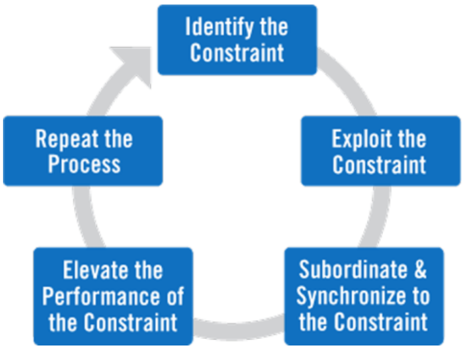


Figure 2: Visualization of the steps in TOC

Mabin (2018) and Şimşit et al. (2014) argue that TOC does not contain 5, but 7 steps. The two additional steps need to be performed before the 5 aforementioned steps. The two additional steps are: (1) Determine the goal of the system (2) Set up measures of the system. If the goal and measures are defined, the 5 steps above can be executed.

3.3 TOC measurement

TOC argues that, in the end, the goal of each company is to earn as much profit as possible. If this is not the company's ultimate goal, it is certainly a critical success factor (Dettmer, 2008). This implies that the output of the system must be money and that the system must be designed in such a way that it generates the highest profit possible. The goal of generating the highest amount of money can be translated to a high net profit, a high Return on Investment (ROI) and a high cash flow. We have introduced measurable terms for the goal, but these measures are calculated at the end of the whole process, so we lack the measures that represent how well the system is performing in terms of its goals during operation time. Goldratt (1999) introduced throughput rate, inventory and operating expenses to be able to measure the performance of any system during operations hours. Those terms are defined differently compared to their definitions in most of the scientific literature (1. Definitions)

If those KPIs represent the goal, there must be a relationship between the net profit, ROI and the throughput rate, inventory and operational expenses. The net profit (1) is expressed as the difference between the throughput rate and the operational expenses, ROI (2) equals the division of the difference between throughput rate and operating expenses by inventory and cash flow equals net profit divided by the increase or decrease of inventory (Naor & Coman, 2013), (Tulasi & Rao, 2012).

(1) $Net\ profit = Throughput\ rate - operation\ expenses$

(2) $ROI = \frac{Net\ profit}{Inventory} = \frac{Throughput\ rate - operation\ expenses}{Inventory}$

(3) $Cash\ flow = \frac{Throughput\ rate - operation\ expenses}{\Delta\ Inventory}$

*The operation expenses and inventory should be measured over the same time period as the throughput rate
*All the variables are expressed in the same units (1. Definitions)

The formulas above show the relationship between the KPIs and the goal. To achieve a high net profit, the throughput rate should be as high as possible and the operating expenses should be as low as possible. To achieve a high ROI, the throughput rate should be as high as possible and the operation expenses and inventory should be as low as possible. To achieve a high cash flow, the throughput rate should be as high as possible and the operation expenses and inventory as low as possible (Tulasi & Rao, 2012). To conclude: the aim of a company is to increase the throughput rate, while decreasing the inventory and operation expenses (figure 3).

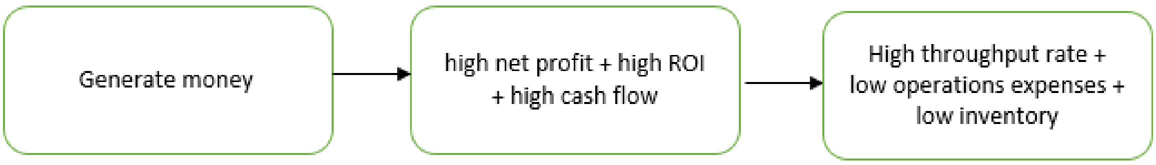


Figure 3: Relationship between earning profit and through put, operations expenses and inventory

3.4 Drum-Buffer-Rope principle

The Drum-Buffer-Rope (DBR) principle ensures that the bottleneck is exploited and the other processes in the system are subordinated to the bottleneck. There are two important factors that affect the system's performance. The first factor is the relation between statistical fluctuation and dependent events and the second factor is the utilization of the workstation capacity of the different workstations in a production line. DBR, takes those factors into account and minimizes their negative effect on the throughput, inventory and operations expenses. An explanation of the two factors is presented below.

Imagine a production line with 5 workstations. Each workstation can start its process, if the workstation before the workstation in question provides the workstation with input or if there still is remaining input in the buffer. This implies that if the output of workstation 1 + the buffer prior to workstation 2 does not meet the potential capacity of workstation 2 at that moment, that the capacity of workstation 2 will not be fully utilized for that time period. Strategically placed buffers can prevent this from happening. On the other hand, buffers are additional costs, so a trade-off between the costs of the buffer and its positive effect on the output should be made.

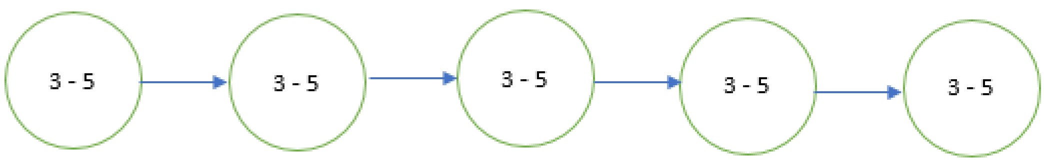


Figure 4: Visualization of a production line consisting of 5 workstations with an output varying between 3 and 5 products per hour

Figure 4 presents a visualization of a production line that will support the explanation of the effect of statistical fluctuation and dependent events. The workstations do not have buffers. The numbers in the circles represent the interval of the output per hour of each workstation, so the output varies between 3 and 5 per hour. The average output will be $\frac{3+5}{2} = 4$. Instinctively, most people would argue that this production line will produce $24 \times 4 = 96$ products per day (assuming a uniform distribution). This is not the case, due to statistical fluctuation and dependent events. Dependent events are events that can only start, if another event has finished. In the production line, each process in the chain is a dependent event of the process prior to the process itself. Furthermore, each workstation shows statistical fluctuation in its output, so with a certain probability the output varies between 3 and 5. The output of the whole chain equals the output the workstation with the lowest output in the chain. This implies that if one of the 5 workstations in the chain has an output of 3, the output of the chain will equal 3 and if and only if, all the workstations in the chain have an output of 5, the output of the chain equals 5. The probability that one of the workstations will have an output below average is higher than the probability that all the workstations will have an output above average, therefore the output of the chain will be below the suggested 4 products per hour. However, if strategic buffers were added to this production line, the negative effect of the statistical fluctuation on the output can be absorbed. More on the buffers 2.5.

The second factor is the utilization of the workstation capacity of the different workstations in the production line.

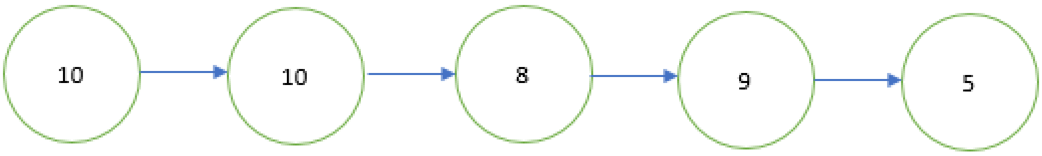


Figure 5: Visualization of a production line (numbers represent maximum capacity)

In the visualization of a production line in figure 5, the circles represent workstations and the numbers in the circles represent maximum capacity per hour and therefore the workstation's maximum output per hour. It seems intuitively that working hard will achieve the goal, however if the workstations in the production line above will work at their 100% capacity Work in Progress (WIP) will accumulate in front of the workstation with maximum capacity 8 and 5, since the input of those workstations is higher than their output. This implies that output of the whole chain is set by the workstation with the lowest capacity. In terms of TOC, inventory and operation expenses are unnecessary high. Inventory is high, because the amount of money spend on intermediate goods in the production line rises and the operation expenses are high, because the workforce of the workstation with maximum capacity 10, 9 and 8 are working harder than required, since the output of the chain will not increase if those workstations have an output above 5. Subordination of the output of those workstations to the output of the workstation with the lowest output will minimize inventory and operation expenses.

3.5 TOC application: Drum-Buffer-Rope

The statistical fluctuation in combination with dependent events and capacity utilization are important factors that influence the output of the production line. It is important to protect the system against the effect of the relation between statistical fluctuation and dependent events and to subordinate the utilization of the workstations to the capacity of the bottleneck. Drum-buffer-rope is TOC production principle that takes those factors into account. It is named after the 3 core elements: the drum, the buffer and the rope. The drum is the constraining workstation in the system. The buffer is a time-buffer, which ensures strategic accumulation of WIP before the drum that protects the drum from statistical fluctuation upstream in the production line. The rope is symbolic for the timing of the release of products by the workstations upstream of the drum.

The drum-buffer-rope application starts with an already identified bottleneck. The bottleneck is the drum, which sets the pace of all the other workstations in the system. Since the bottleneck determines the output of the whole system, the bottleneck should always work on its full capacity to achieve maximum output of the system. In other words: “the bottleneck should be exploited”. Exploitation of the drum is achieved with the use of a time-buffer. The buffer is the time interval that predates the release of work relative to the date on which the constraint will process the work. This differs from the more common perception of a buffer, which is measured in terms of physical goods. The time buffer in the TOC will, however, result in an accumulation of physical goods in front of the bottleneck for a large percentage of the operating time of the system. This accumulation protects the drum from statistical fluctuation upstream of the production line. When determining the length of the time buffer, the statistical fluctuations should be considered. This implies that the buffer should be longer than the sum of the waiting time in the queue + the average processing time of all the workstations upstream + the variance of the processing time of all the workstations upstream. This is a very simplified description of how to determine the buffer length. Ye and Han (2008) have developed mathematical models to determine the buffer length. The time buffer ensures that the bottleneck will always be working.

We protected the drum, now it is time to protect the system by subordinating all the workstations to the drum. Subordination of the processes to the drum is key to inventory reduction. The buffer must be stable; thus, the system’s input must equal the drum’s output. If the bottleneck is not working for a period of time, this must be reflected in the system’s input, otherwise the WIP will increase each time the bottleneck is in down-time. This is the job of the constraint rope. The constraint rope can be seen as a real-time feedback loop between the drum and input of the system. The constraint rope coordinates the input of the system with the output of the drum.

Until now we have discussed the part upstream of the bottleneck. Now it is time to discuss the part downstream of the bottleneck. The output of the system must be on time. To ensure that the output is on time, we introduce the shipping buffer. The shipping buffer is the time interval that predates the release of work relative to the date on which the product should be shipped. The definition is the same as with the bottleneck buffer, but it covers a different part of the system. Again, to prevent accumulation of inventory, we will need a mechanism that relates the market demand with the drum. This mechanism is the shipping rope and it works according to the same principles as the constraint rope.

3.6 TOC application: the thinking processes

The Thinking Processes (TPs) tools are a set of logic diagrams that are used to answer the 3-fundamental questions in TOC: (1) What to change? (2) What to change to? (3) How to change? The TPs can be used individually or in combination. The TPs consists of five logic diagrams:

(1) Current Reality Tree (CRT)
(2) Future Reality Tree (FRT)
(3) Prerequisite Tree (PT)
(4) Transition Tree (TT)
(5) Evaporating Cloud (EC), also referred to as the Conflict Resolving Diagram (CRD)

The CRT, FRT and TT are build up by constructing connections between observed effects and their causes based on ‘sufficient cause’. A cause is a sufficient cause if the cause inevitably leads to a certain consequence. An example: ‘if it rains, the earth gets wet’. In this case, the rain is a sufficient cause for a wet earth. The PT and EC both use necessary condition thinking. Condition A is a necessary of condition B if condition A is necessary to achieve condition B. An example: a bike (A) is necessary to cycle to school (B).

The problem analysis in the TOC methodology is based on the assumption that undesired effects exist because of a few number of root causes. The TPs identify those root causes and offer solutions to eliminate them. (Librelato & Lacerda & Rodrigues, 2013). The purposes of the individual TPs and the relationship between the fundamental question and the TPs are presented in figure 6.

Central Question	Tools	Target
What to change?	Current Reality Tree – CRT	The essential goal of the Current Reality Tree (CRT) is the definition of the central problems found in a specific system
What to change it into?	Evaporating Clouds – EC	The Evaporating Clouds aim at verbalizing assumptions that cause the central problems, seeking innovative solutions (injections)
	Future Reality Tree – FRT	The goal is to ensure the effectiveness of the solution and check the positive and the negative effects that may arise
How to cause the change?	Prerequisite Tree – PRT	The Prerequisite Tree is used to split the injection well. Intermediate goals that must be achieved so that the injection is implemented are set
	Transition Tree – TT	The Transition Tree is responsible for setting up an action plan objective, seeking to eliminate the core problems identified above

Figure 6: Relationship between TPs and the 3 fundamental questions in TOC

(Librelato & Lacerda & Rodrigues, 2013)

3.6.1 Current reality tree

The current reality tree is a logic diagram that is used to find the root-cause of a problem. The CRT is based on cause-effect logic. It aims to identify the cause that is responsible for most of the Undesired Effects (UDEs). By focussing on that particular cause, we can address multiple UDEs at the same time. The use of the CRT will help to identify physical as well as non-physical constraints.

Setting up a CRT starts with identifying all the undesirable effects (UDEs). The next step is to examine the cause-effect relations between the UDEs. The easiest way to do this is to set the UDE that does not cause an other UDE at the top of the CRT and work downwards to find the root-cause of the UDEs in the CRT. When examining the relationships between the UDEs it is important to distinguish between the following cause-effect relations (Scoggin & Segelhorst & Reid, 2003):

- 1 UDE can be the cause for multiple UDEs
- multiple UDEs, together, are the cause of one UDE
- 1 UDE can be the cause for another UDE

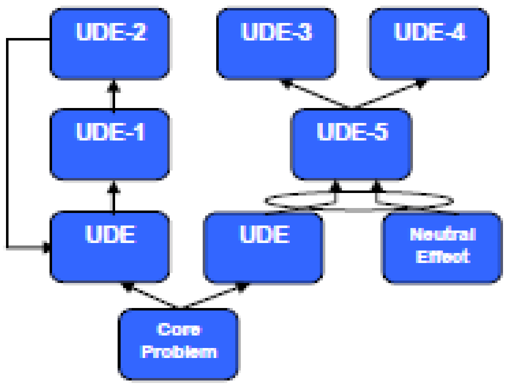


Figure 7: Hypothetical CRT

In the graphical representation of the hypothetical CRT (figure 7) ellipses represent an 'AND' relation, which means that the causes, together, result in the effect. Neutral effects are effects that are, on itself, neither positive nor negative, but cause a UDE. Neutral effects can be added to create a better representation of reality in the CRT (Based on: Scoggin & Segelhorst & Reid, 2003) (Based on: Umble & Murakami, 2006).

3.6.2 Evaporating cloud

The Evaporating Cloud (EC) or the Conflict Resolving Diagram (CRD) is used to 'evaporate' or 'resolve' a conflict between ideas or opinions. A conflict can exist in many scenarios; therefore, the EC can be used in many situations. The EC consists of 'wants', 'needs' and an 'objective'. The conflicting 'wants' of two people, are the result of their 'needs' and those needs should be in line with a common objective.

The CRT has been used to identify the core problem that needs to be addressed. In most of the cases the core problem is caused by two conflicting 'wants' of two people. TOC offers the evaporating cloud to resolve this conflict and turn it into a desirable solution for all the parties involved. The EC is based on the assumption that conflicts are the result of believing an incorrect assumption, therefore conflicts can be solved by correcting the incorrect assumption. The EC helps to do so. It examines the logic behind the conflict and its underlying assumptions. (Based on: Chaudhari & Mukhopadhyay, 2003)

Setting up the EC starts with the two conflicting 'wants'. The two conflicting 'wants' are a result of the two conflicting 'needs'. The needs are necessary to meet a certain objective. I want D, because I need B/C to meet A (figure 8).

The next step is to add the assumptions on which the relationships (denoted by the arrows) are based. One of the assumptions will be incorrect and therefore the initially seeming logical relationship will not be so logical anymore and the conflict will be resolved. Finding the incorrect assumption will help to find an injection (solution). The evaporating cloud ensures that the user thinks critically of all the components in the conflict and challenges the assumptions that are made.

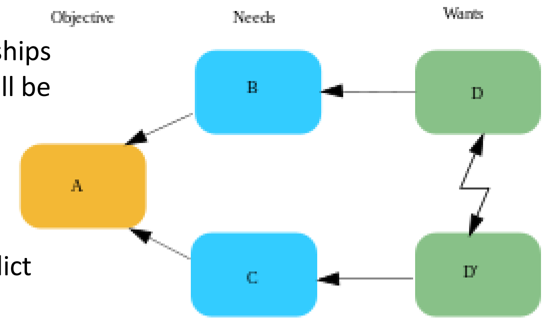


Figure 8: Hypothetical Evaporation Cloud

3.6.3 Future reality tree

The Future Reality Tree (FRT) is used to examine the effectiveness of the solution that has been found with the use of the EC. Basically the injection (solution) that comes out of Evaporation Cloud is added to the CRT. The logic behind the FRT is that, the moment that the injection is inserted in the CRT, UDEs should turn into Desirable Effects (DEs) based on valid cause-effect logic. By doing so, the FRT serves as a tool to evaluate the effectiveness of the injection. (Based on: Scoggin & Segelhorst & Reid, 2003)

3.6.4 Prerequisite tree

The aim of the Prerequisite Tree (PT) is to set up the goals of the implementation plan of the solution. It allows us to overcome the obstacles that stop us from implementing our plan. Setting up the Prerequisite Tree starts with the injection that came out of the analysis of the EC. Each injection requires its own PT. The next step is to determine the obstacles that hinder us from implementing the injection and by determining the obstacles we can simultaneously determine the intermediate objectives. The last step is to decide the order in which the intermediate objectives should be met, which is the same as deciding on the order in which the obstacles should be overcome. This order is set by necessity logic: intermediate objective A should be met before objective Q can be met.

3.6.5 Transition tree

The transition tree is a tool that sets the actual implementation plan. It connects the intermediate goals to actions based on if-then logic and sets the order in which the intermediate objectives should be met. It also adds a reason on why the action will result in meeting the demand. (Based on: Scoggin & Segelhorst & Reid, 2003)

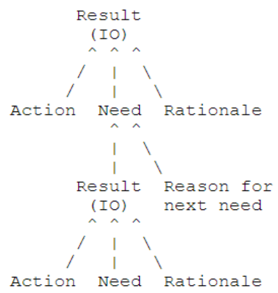


Figure 9: Transition tree

3.6.6 Conclusion literature review

<u>Sub2-RQ2:</u> How to apply the Theory of Constraints to (1) identify the constraint and (2) increase the constraint's capacity?

The Theory of Constraints offers a framework for continuous improvement.
The process starts with a goal and measurement. The end-goal of each company is to earn money. In the production scene, this goal can be measured by measuring throughput, operation expenses and inventory. When the goal and the measurement is set, the bottleneck of the system must be identified. Second, the bottleneck should be exploited. Third, the other processes should be subordinated to the bottleneck. The fourth step is to elevate the constraint. The identification of the bottleneck can be conducted by an analysis of the measure 'throughput' in combination with a Current Reality Tree. The subordination and exploitation phase can be executed through the application of the Drum-Buffer-Rope principle. The evaporation cloud can be used to determine the appropriate injection (solution) to address the problem in the elevation phase. The future reality tree provides a check-up of the effectiveness of the injection based on cause-effect logic. Lastly, the prerequisite tree identifies the obstacles and intermediate objectives for the implementation of the injection and the transition tree draws up the implementation plan.

4 Production line analysis

4.1 Process description of the M-93

The steps below present the process of the M-93 from coil to a bundle of tubes in the outside storage.

1. The input of the production process is a coil (1. Definitions) and the output is a bundle of tubes.
2. The coil, which is the input product, goes through the slitting machine to get the right proportions depending on the tube produced. The output of the slitting machine is a rolled up narrow strip, this intermediate good will be referred to as ‘ring’.
3. The ring gets transported to the decoiler, which unwinds the ring.
4. The narrow strip goes through the straightening machine, which straightens the narrow strip. Before the straightening machine, the narrow strip tends to bend, because it has been rolled up.
5. The MIG welder welds the previous ring of narrow strip to the new ring of narrow strip. This ensures that the tube production is a continuous process.
6. The ring gets unrolled. A buffer is created. The buffer is needed, because the MIG welding takes time and the aim of the production line is to have continuous stream output.
7. The narrow strip in the buffer gets pulled out of the buffer into the edge bender. The edge bender bends the edges of the narrow strip. The bended edges are required for the HF welding, later in the production line.
8. The narrow strip goes through the CTA and Finpass, which roll the steel into a round profile.
9. HF welding of the tube. The two sides are welded together. A round tube is created.
10. Cooling down of the hot tube
11. The tube goes through a calibration machine. If required the machine forms the round tube into a square or rectangular one.
12. The saw makes sure the tube has the right length
13. The singular tubes with the right profile and length are bundled together with 1, 4 or 6 extra tubes
14. The tubes are drained. During the production process, the tubes are sprayed with an emulsion. This emulsion is environment unfriendly, therefore they need to be drained.
15. The tubes are transported to the outside storage.
    NOTE: Figure 10 shows a visualization of the production process of the M-93. The numbers refer to the steps above.

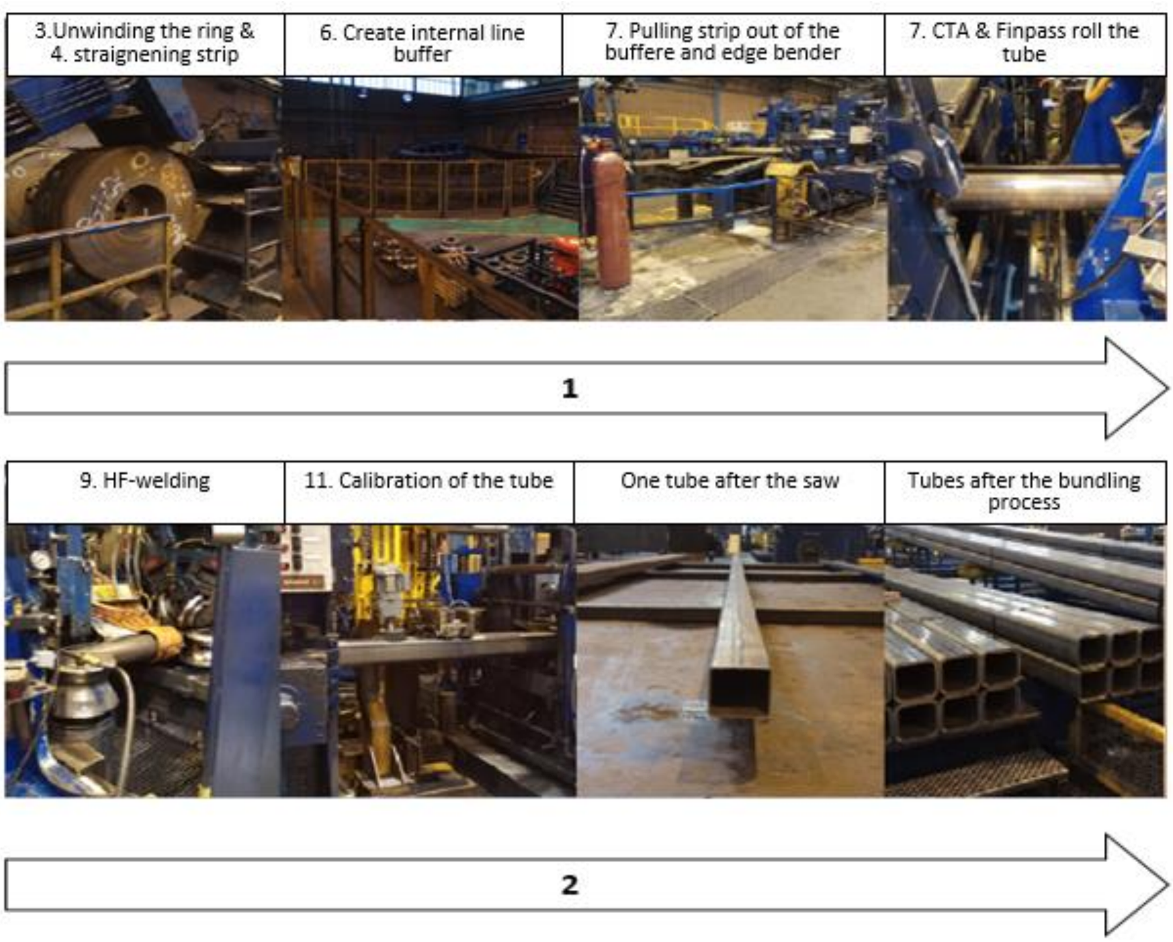


Figure 10: Process visualization

4.2 Data gathering: processing speed

The research variable 'processing speed per workstation for the tubes in the research scope in meters of tube per minute' has been used to identify the bottleneck. Meetings with experts on the M-93 identified potential bottleneck workstations. The potential bottlenecks are the workstations between the tubemill and the outside storage, which is obvious since the output speed is constrained by one of the workstation between the tube mill and the outside storage as stated in the introduction. The workstations in the research population are:

- Tube mill (consisting of the CTA, Finpass, HF-welding, calibration and saw)
- Bundling process
- Draining process
- Transportation process

The tube mill is added to the research population, since the bottleneck should meet the tube mill's processing speed.

4.2.1 Tube mill

The maximum processing speed of the tube mill is already measured by Tata Steel Tubes. This data is presented in appendix A. The data has been validated with an interview with Eric van de Steen. The data shows 2 important patterns:

1) When the wall-thickness increases, the production speed decreases. This is due to the fact that the HF-welding of the tubes takes more time when the wall thickness of the tube increases, because the two surfaces that have to be welded together become bigger.

2) When the diameter of the tube increases, the production speed decreases, because the width of the narrow strip increases when the diameter of the tube increases. The increased width of the narrow strip implies that the welding torch, which welds the previous ring to the new ring, covers a longer distance, which takes more time.

4.2.2 Bundling process

The bundling process involves 3 machines: the MAIR and 2 strapping machines. The MAIR creates the shape of the bundle, by stacking the required number of tubes in the desired order. After the bundle shape is created, the tubes are strapped with several straps, depending on the tube type. The two strapping machines work simultaneously. The necessary number of straps depends on the length and weight of the tubes in the bundle. In the case of the tubes in this research scope, currently, 6 straps are necessary.

To create the shape of the bundle, the MAIR places a layer of tubes on top of another layer with the use of a magnet. In case of the first layer, the MAIR places the layer of tubes on the bottom of the machine. A layer can consist of multiple tubes depending on the diameter of the tubes, because the magnet has a fixed length. The process of the MAIR consists of the following steps:

(1) Start in the start position
(2) Move to the queue of tubes and pick up the necessary number of tubes for 1 layer
(3) Move the layer into the machine
(4) Return to the start position

This cycle takes 25 seconds and is repeated until the necessary shape has been created. The tubes in research scope are bundled with 2 tubes in one bundle (24 meter of tube). The MAIR can pick up two tubes at the same time, therefore it needs to create one layer and since one layer takes 25 seconds, the MAIR has a processing speed of $24 \ * \left(\frac{60}{25}\right) = 57.6$ meters of tube per minute. Figure 11 shows a visualization of the process of the MAIR.

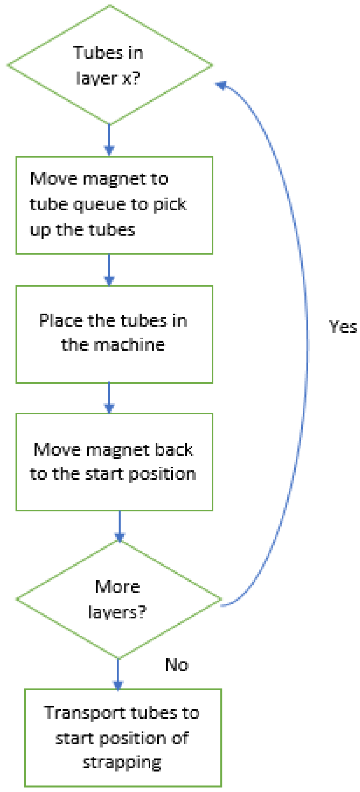


Figure 11: Flowchart of the process of the MAIR

When the bundle shape is created, it is transported to the 2 strapping machines, which strap 2 straps simultaneously. 6 straps are used, so one bundle needs to pass the two machines 3 times. One cycle, that starts when the bundle is transported to the strapping machine and ends when the bundle has left the strapping machine, takes approximately 70 seconds. In those 70 seconds, the strapping machine processes 24 meters of tube, which implies a processing speed of approximately 21 meters of tube per minute.

The measures above, already existed at Tata Steel Tubes. I validated them with time-samples.

4.2.3 Draining process

The draining process quickly drains the accumulated emulsion of two bundles by lifting one side of each bundle; the emulsion flows to the lower side. When the bundles are strapped they are moved to the queue in front of the draining process. When the second bundle enters the queue, a sensor sends a signal to the computer which lowers the draining bundles and moves those to the bundle stacking process. Simultaneously, the tubes in the draining queue move to the draining machine and the whole cycle starts all over again. The important thing to note is that, in the current reality, the draining time depends on the number of bundles in the queue; at Tata Steel Tubes it is assumed that the time it takes for 2 tubes to enter the draining queue is always bigger than the time it takes to sufficiently drain a bundle of tubes. When the bundles enter the queue at a fast pace, the draining time becomes shorter, since the sensor is activated more frequently. Since the draining time is dependent on the number of bundles in the queue and therefore dependent on the speed at which the bundles arrive in the queue, the draining process cannot be a bottleneck.

4.2.4 Transportation process

The transportation process is a difficult process to analyse, because it is not an automated process and fully initiated by the Tata Steel Tubes' workforce, which makes it prone to variability on its speed performance. The transportation process follows the following steps:

(1) An X number of bundles of tubes are stacked together and lifted on a truck.
(2) The truck drives the stack of bundles to the outside storage
(3) The stack of bundles is lifted from the truck, by a forklift and placed in the outside storage.
(4) The truck returns to the M-93 to pick up a new stack of bundles.

Time estimations of each step in the process are displayed in figure 12 and 13. The estimations are ranges that indicate the smallest and largest time one step in the transportation process can take. The transportation process differs between the 323 and 273 in the loading capacity of the truck. The loading capacity of the 323 is 192 meters of tube and the loading capacity of the 273 is 384 meters of tube. Furthermore, in case of the 273 it is impossible to load all the tubes at once, therefore it takes two hoists. Loading the 323 tubes only takes one hoist. In figure 12 and 13, the red bars show the lowest time each step in the process can take and the grey bars show the longest time each step in the process can take. The actual time will be somewhere in the middle. The diagrams sum up the smallest and longest times and by doing so it shows the time the transportation process takes in the worst-case and best-case scenario. These scenarios are quite unlikely to happen, since the probability that all the steps in the transportation process are in their worst-case or best-case scenario is low.

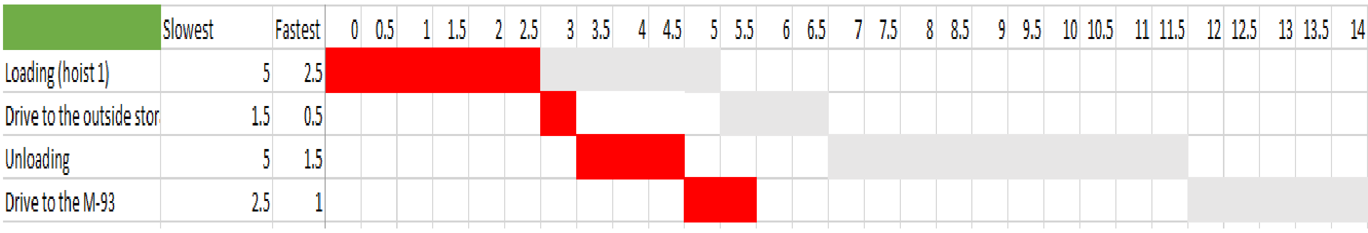


Figure 12: Timeline transportation process of the 323

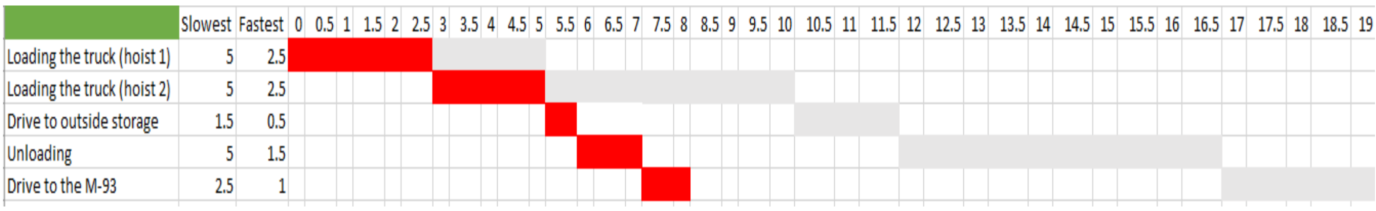


Figure 13: Timeline transportation process 273

Tata Steel Tubes has one truck that can transport the tubes from the M-93 to the outside storage. This truck also transports the output of the M-92 tube mill, thus it must divide its operating time between the M-93 and M-92. The truck has an availability of 30%-50% for the M-93 (based on an estimation of Chris). This greatly reduces the effective transport speed. If the transportation process cannot handle the output rate of the M-93, one of the trucks of International Transport BV Van Meeteren is used to support the truck of Tata Steel Tubes. The extra truck increases the capacity of the transportation process drastically as can be seen in the table 3. If needed, Chris will even add a second truck to increase the capacity even further (based on the interview with Chris).

Table 1: processing speed transport per capacity scenario

Tube	Speed in meter per minute (m/m) Tata Truck availability 30%	Speed m/m Tata Truck availability 50%	Speed m/m Tata Truck availability 30% + Chris' Truck	Speed m/m Tata Truck availability 50% + Chris' Truck
323	5.9	9.8	25.6	29.5
273	8.5	14.2	36.9	42.6

Since the processing speed depends on the truck availability of Tata Steel Tubes and on Chris' decision to use one of his own truck, the processing speed is not stable. This could lead to potential problems, since the output speed of the M-93 is stable. I will explain this with an example. Suppose the M-93 produces tubes at a rate of 21 meter of tube per minute (which is the current reality, when producing 323 and 273) and in the initial stage, the transportation to the outside storage solely relies on the Tata Steel Tubes' truck. The Tata Steel Tubes' truck does not have enough capacity and Chris might have to decide to increase the transport capacity by using one of his own trucks. However, there is a set up time for Chris' truck to become fully operational and since the M-93 produces at a constant rate, the transportation process could, potentially, hinder the production speed of the M-93. However, this is not the case, because Tata Steel Tubes created a buffer storage next to the M-93. When the transportation process does not have enough capacity temporarily, the tubes are moved to the buffer storage, so the buffer storage eliminates the negative effect of the varying capacity of the transportation. The buffer has a storage capacity of 6144 meter of tube. If the M-93 is producing with an average speed of 21 meter of tube per minute and all the tubes are placed in the buffer storage, the buffer storage is full after approximately 4.5 hours (which is never the case, since the Tata Steel Tubes truck has an availability of 30%-50%). This simple calculation shows that the buffer storage has enough capacity to minimize the effect of the changing transportation speed. If the buffer's utilization starts to approach 100%, Chris can easily decide to use on of his own trucks to empty the buffer storage.

The analysis of the transportation process is not so easy to quantify, because of the differing scenarios that can exist. As explained above, those scenarios depend on the tube type, the Tata Steel Tubes' truck availability and Chris' decision to increase the transportation process' capacity with one of his own trucks. This leads to varying values of the processing speed of the transportation process (table 1).

4.2.5 Processing speed analysis

This cross-case analysis will compare the processing speed of the tube mill, bundling process and the transportation process to identify the bottleneck workstation.

Table 2: Processing speed per workstation in the research population

		Tube-rolling mill	Bundling process	Transport			
Diameter	Wall-thickness		12m	TATA truck (30%)	TATA truck (50%)	Tata truck (30%) + Chris	Tata truck (50%) + Chris
273	4	50	21	8.5	14.2	36.94	42.64
273	4.5	50	21	8.5	14.2	36.94	42.64
273	5	50	21	8.5	14.2	36.94	42.64
273	5.6	45	21	8.5	14.2	36.94	42.64
273	6	45	21	8.5	14.2	36.94	42.64
273	6.3	45	21	8.5	14.2	36.94	42.64
273	7.1	30	21	8.5	14.2	36.94	42.64
273	8	30	21	8.5	14.2	36.94	42.64
273	10	20	21	8.5	14.2	36.94	42.64
273	12.5	20	21	8.5	14.2	36.94	42.64
323.9	4	35	21	5.9	9.8	25.6	29.5
323.9	4.5	35	21	5.9	9.8	25.6	29.5
323.9	5	35	21	5.9	9.8	25.6	29.5
323.9	6	35	21	5.9	9.8	25.6	29.5
323.9	6.3	35	21	5.9	9.8	25.6	29.5
323.9	7.1	35	21	5.9	9.8	25.6	29.5
323.9	8	30	21	5.9	9.8	25.6	29.5
323.9	8.8	25	21	5.9	9.8	25.6	29.5
323.9	10	20	21	5.9	9.8	25.6	29.5
323.9	12.5	20	21	5.9	9.8	25.6	29.5

Table 2 shows the current values for the research variable 'processing speed per workstation for the tubes in the research population in meters of tube per minute' The data is gathered through interviews, an analysis of previous studies and an analysis of in-line processing data.

The process corresponding to the column with the lowest value is the constraining workstation. This obviously is the Tata Truck with an availability of 30%, however as described in the transportation paragraph above, the transportation capacity varies which implies a differing processing speed. If needed, Chris increases the capacity with one truck, which increases the processing speed with 19.7 meter per minute as can be seen in the table above. So, the 'true' processing speed of the transportation process is described by the columns 'Tata truck (30%) + Chris' and 'Tata truck (50%) + Chris'. The combination of the buffer storage and the varying capacity excludes the transportation process from being the constraining factor.

Based on the data in the table, the bundling machine is the constraining factor that limits the output speed of the chain, because compared to the other workstations it has the lowest processing speed for most of the tubes. There is one exception, which are the tubes with a wall-thickness above 10 mm, but if further research is conducted to increase the processing speed of that workstation, the output will still be limited by the bundling process. So, we can conclude that the constraining workstation is the bundling process. The next chapter will deep-dive into the bundling process to gain a deeper understanding of the workstation and its limitations.

4.3 Deep-dive research into the bundling process

In 3.3, the distinction between the MAIR and strapping machine has been made. The MAIR creates the bundle shape and the strapping machines strap the tubes in the bundle together. This description is a simplification of the actual process. Figure 11 in 3.2.2. shows a flowchart of the process of the MAIR.

The processing time of the MAIR depends on the number of layers the bundle shape requires; placing one layer takes 25 seconds, so an x number of layers takes x * 25 seconds. The 323 and 273 are bundled with two tubes in one bundle. The 2 tubes are 1 layer; thus, it takes 25 seconds. The processing speed of the MAIR is (60/25) *24 = 57.6 meter of tube per minute. This is a very high processing time, if we compare it to the processing times of the other workstations (cross-case analysis paragraph). Therefore, the MAIR cannot be the constraining factor.

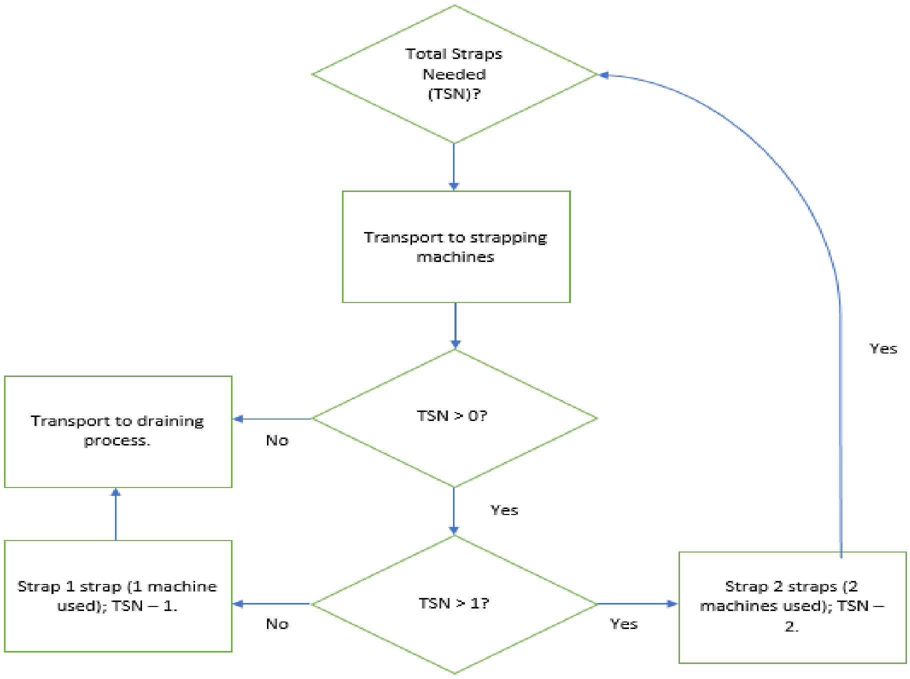


Figure 14: Logic of the number of straps needed and the number of cycles

The processing time of the strapping machine depends on the number of straps needed to strap one bundle of tubes, which depends on the length and weight of the tubes in the bundle. Figure 14 visualizes the relation between the number of straps and processing time: the more straps needed, the more steps the bundle of tubes needs to go through, which implies a longer processing time.

In the case of the 273 and 323 with a length of 12 meter, 6 straps are used, so the bundle needs to pass the two strapping machines 3 times. The bundle goes through the following steps:

(1) Transport 1 (T1): transport to the strapping machines. The bundle is placed in the machines and is ready to be strapped.
(2) Strapping 1: The bundle is strapped for the first time.
(3) Transport 2 (T2): The bundle moves in the strapping machines and is positioned for the strapping of the second pair of straps. During transport 2, the strapping machines are refilled with new strapping material.
(4) Strapping 2: The bundle is strapped for the second time.
(5) Transport 3 (T3): The bundle moves through the strapping machines and is positioned for the strapping of the third pair of straps. During transport 2, the strapping machines are refilled.
(6) Strapping 3: The bundle is strapped for the third time.
(7) Transport 4 (T4): The bundle is finished and is transported to the draining queue

The total process takes 70 seconds, which implies a processing speed of 21 meters of tubes per minute. Therefore, the processing speed of the whole bundling process equals 21 meters of tube per minute.

Time samples of each step in the strapping process have been gathered to gain a deeper understanding of the process performance. Figures 15 and 16 present the processing time of each of the steps involved. Figure 15 shows the first 35 seconds and figure 16 shows the second 35 seconds. As shown in the figures, some processes take place simultaneously (transport and refilling the strapping machines).

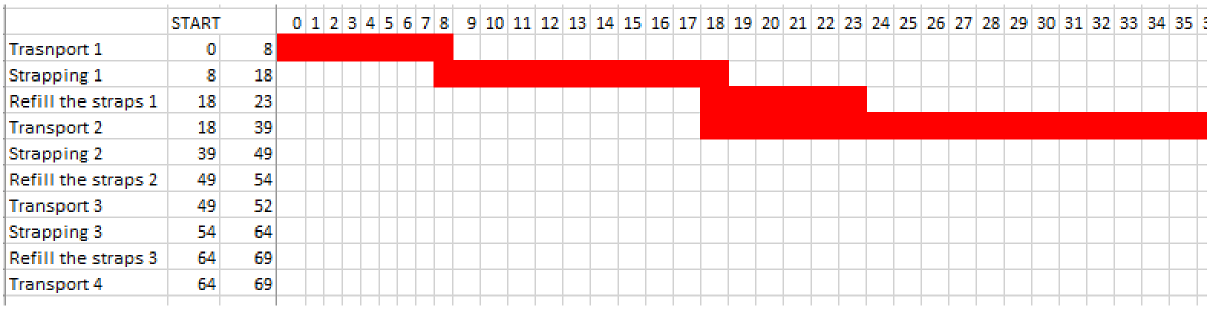


Figure 15: Timeline strapping process; interval 0-35 seconds

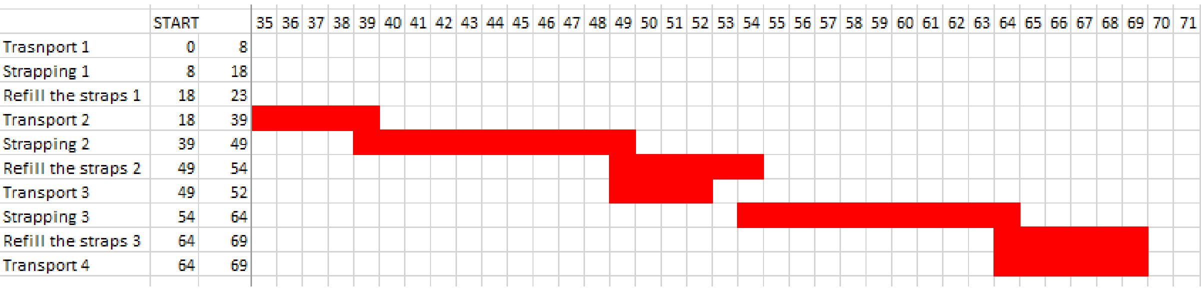


Figure 16: Timeline strapping process; interval 35-70 seconds

Looking at figure 15, it becomes evident that transport 2 takes a relatively long time. It takes 21 seconds, which is 27 % of the total processing time. In those 21 seconds the bundle of tubes is transported over 3.5 meters. Covering those 3.5 meters, take 21 seconds, because the strapping process is hindered by the process downstream of the strapping machines: placing of the previously strapped bundle in the draining queue. Normally it would take approximately 5 seconds to cover 3.5 meters, due to the hinder it takes 21 seconds. Another important thing to note is that one cycle of strapping (placing + refill) takes 15 seconds in total, which is 21% of the total strapping time. The bundle of tubes needs to go through 3 cycles, which adds up to 45 seconds of strapping.

So far, the focus has been on the processing time. This paragraph will focus on the other variable that affects the speed: meters of tube processed. When bundling 2 tubes in one bundle, only 24 meters of tube are processed. 24 meters of tube in one bundle is a very short length compared to other production scenarios. The processing time does not depend on the number of tubes per bundle, so ideally, we would bundle as many tubes as possible. The ‘solution generation’ chapter goes into whether this is possible or not.

4.4 Current Reality Tree

Figure 17 contains the current reality tree of the strapping process. All the red rectangles are the Undesired Effects (UDE). The cause-effect relations are described by the arrows between the UDEs

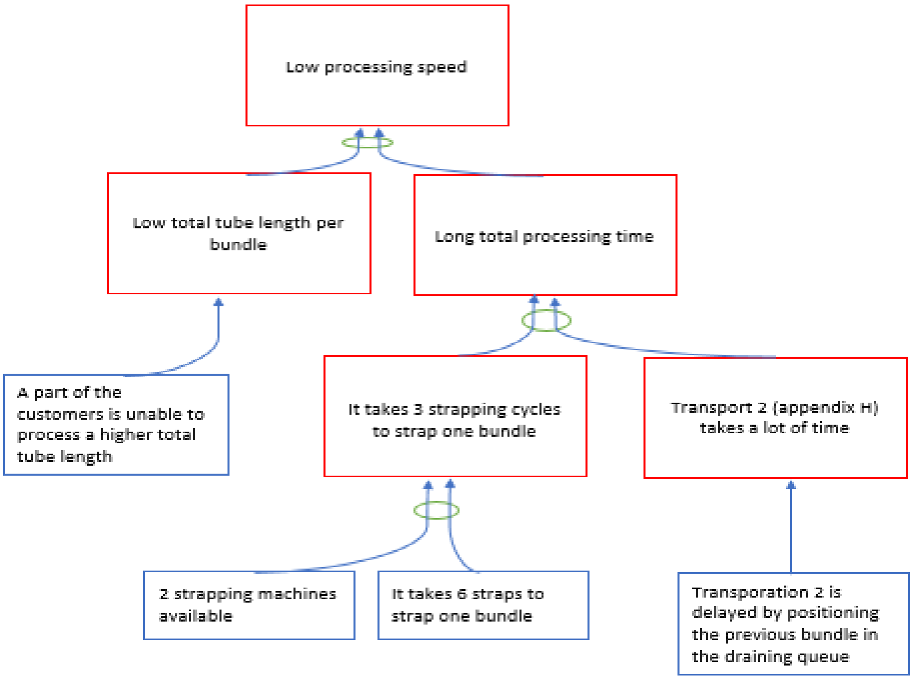


Figure 17: Current reality tree of the strapping process

The UDEs are presented in the red rectangles. The cause-effect relationships between the UDEs have been added, as well as some 'neutral causes'. The neutral causes (in blue) are the arguments that Tata Steel Tubes has given me for their design of the strapping process. These arguments will be re-evaluated in the solution generation chapter, since they might be invalid.

The current reality tree presents 3 potential problems:

1. low total tube length per bundle
2. strapping cycles per bundle
3. transport 2 takes a lot of time.

It also shows the relationship between processing time, total tube length per bundles and processing speed, which will be used in the solution generation chapter.

4.5 Intermediate conclusion: RQ1

RQ1: What is the cause of the underperformance on the speed at which the tubes arrive in the outside storage of the M-93 at Tata Steel Tubes?

The output speed of the M-93 is set by the bottleneck of the M-93. The workstations in the research population have been analysed on their performance on the processing speed, which determines the throughput of each workstation. The bundling workstation has a processing speed of 21 meter per minute and therefore it has been identified as the constraining workstation. The bundling process consists of two processes: creation of the bundle shape (MAIR) and strapping the bundle. The bottleneck turned out to be the strapping process. Time samples of the strapping process were taken and a timeline was set up. The timeline provided insights in the critical steps in the strapping process. Additionally, a current reality tree was used to outline the cause-effect relations between the undesired effects and (root)causes. The analysis led to multiple causes of the problem. However, the most prominent factor is that the strapping process is hindered by the subsequent step in the production line (placing the bundle in the draining queue). The distance between the strapping process and the draining queue is very small and when the bundle is strapped, it moves through the strapping machines which results in the bundle to protrude to either the MAIR-side or the draining-side of the machine. Since the distance, between the strapping machine and the draining queue is rather small, the bundle cannot protrude to the draining-side too much, when the previously strapped bundle is being processed. This is orchestrated by sensors. At the moment, the process of placing the bundle in the draining queue takes up too much time, therefore the sensor that measures the activity of the draining queue and the extent to which the bundle protrudes to the draining-side of the strapping process is activated. Activation of the sensor, stops the strapping process until the previously strapped bundle is placed in the draining queue. Additionally, the following constraining factors have been identified: (1) low total tube length per bundle (2) It takes 3 strapping cycles to strap one bundle, which results in a high strapping time.

5 Solution generation

The aim is to increase the processing speed of the strapping process such that it meets the processing speed of the tube mill (appendix A). The CRT sets the direction to achieve this aim:

1. Decrease the time interval in which a certain amount of tubes is processed
2. Increase the amount of tubes that is processed during a constant time interval.

The CRT shows the following potential conflicts:

1. Increase total tube length, to increase speed versus not increase total tube length, because some customers cannot process bundles with a higher total tube length.
2. Add an extra strapping machine, to increase processing speed versus not add an extra strapping machine, because of extra costs.
3. Use less straps to strap one bundle to decrease processing time versus strap with the current number of straps, because of the strap strength.

The CRT also points to another improvement possibility to decrease the processing time: decrease T2. The interventions can be implemented as a combination or individually.

5.1 Evaporation clouds

Setting up de EC start with the conflicting wants that result from two needs that both should serve the overall objective. In the previous chapters, the goal is described as an increase in processing time of the bottleneck such that it will meet the processing speed of the tube mill. The motive behind this goal is to produce more tubes and by doing so, earn more money. The objective used in the ECs is 'earn more money'. This decision has been made, because the analysis of the conflicting arguments will be more accurate. If the arguments were analysed based on the objective to increase the processing speed, some profit affecting factors would be excluded from the analysis and the achievement of the overall aim would be in jeopardy.

5.2 Bottleneck: downstream process hinders strapping

The most prominent constraining factor is the delay of Trasnport 2 (T2; figure 15). T2 is delayed, because the previously strapped bundle must be placed in the queue of the draining process. Starting from the point in time where the new bundle can enter the strapping machine, it takes approximately 39 seconds until the second pair of straps can be strapped (figure 18). The steps that must be taken to place the previously strapped bundle in the draining queue are:

1. Further transport, such that the strapped bundle is accurately placed in front of the draining queue
2. Lifting the strapped bundle by lifting the whole conveyor belt, such that the horizontal transport toward the draining queue is possible
3. Horizontal transport to the draining queue.
4.
5. Lowering the conveyor belt to receive the next strapped bundle.

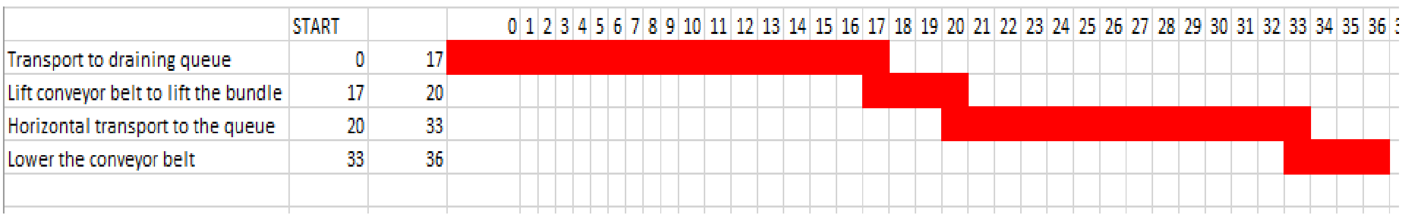


Figure 18: Timeline of placing the previously strapped bundle in the draining queue

A timeline based on samples can be found in figure 18. The total time it takes to place the previously strapped bundle in the draining queue is approximately 36 seconds. It is important to note that T2 is only hindered by placing the previous bundle in the draining queue if the subsequent bundles follow each other closely, which only is the case when the strapping process is the bottleneck.

The transport from the strapping machine to the draining queue (in figure 18: ‘transport to draining queue’) takes up 47% of the total processing time. The average transport time to the draining queue is 17 seconds. One of the reasons that it takes so much time is that the inline transportation of the strapping machine is connected to the transportation to the draining queue. Both the transportation processes are driven by the same computer. The result of this connection is that when the transportation in the strapping process stops, the transport to the draining queue stops as well. This is problematic, because the moment that the bundle is strapped, which implies that the bundle in the strapping machines is stopped, the transport to the draining queue is stopped. This is unnecessary. If two independently driven transport sections are created, one inline transport section for the strapping process and one transport section to the draining queue, stopping the strapping process will not result in stopping the transport to the draining queue. The transport could be orchestrated by a variable frequency drive, which regulates the operating speed more fluently than the current reality (two options: on or off). A small engine is used to lift the conveyor belt. The processing time of lifting and lowering the conveyor belt can be decreased by changing the gear ratio. This might imply that a stronger engine is needed. Figure 18 shows that the lifting and lowering of the conveyor belt only takes up 6 seconds (in total), which is approximately 17% of the total cycle time. An engine in combination with a pulse counter is used to transport the bundle horizontally toward the draining queue. The engine has enough capacity to increase the transportation speed, however the pulse counter will not be accurate enough and since it measures the distance over which the bundle is transported it must be accurate. Transporting the bundle horizontally takes up 36% of the total processing time. All the information above is gathered in an interview with Jacco Jansen and through time sampling. Splitting up the transportation in two sections (strapping and draining) and a more accurate pulse counter will have the biggest impact, because the steps affected by those interventions take up the biggest part of the total processing time. I assume that the processing time of placing a bundle in the draining queue can be decreased with 25%, if the transport speed to the draining queue and the horizontal transport speed are increased. In the current situation, the bundle in the strapping machine is approximately hindered for 16 seconds by the placing of the previous bundle in the draining queue. A decrease in processing time of 25% implies that the time the bundle is hindered decreases to approximately 6 seconds. Ideally, the bundle is not hindered at all. To achieve the situation the processing time of placing a bundle in the draining queue should be decreased by 40%. Further research should be conducted to determine whether a decrease of 40% is achievable.

The intervention proposed above, could easily be combined with one of the proposed improvements below. These combinations will be evaluated in the experiments of the simulation study (described further in the report).

5.3 Additional improvement possibility 1

Additional improvement possibility 1 is to increase the total tube length per bundle. The following paragraphs are limited to an increase from 2 to 5 tubes in one bundle. If Tata Steel tubes wants to increase the number of tubes in a bundle above 5 tubes per bundle, it must invest a lot of money. The MAIR must be redesigned and it will lead to a lot of problems in the transportation process. Three and four tubes in one bundle will pose a lot of problems in the transportation of the tubes, because the stacked bundles will become unstable.

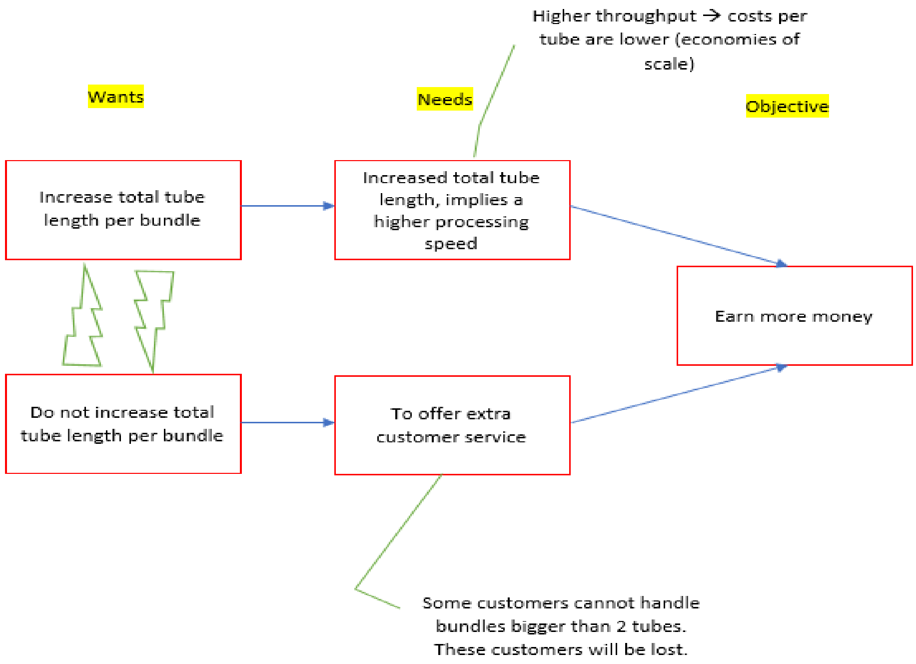


Figure 19: Evaporation cloud on additional tube length

The Evaporation Cloud in figure 19 was set up to evaluate the arguments that Tata Steel Tubes presented me and to create an overview of the restrictions involved in the decision to come up with the most effective solution considering the restrictions.

There are two restrictions to this intervention:

1. The solution is applicable for the 323 and 273 for a wall thicknesses up to 5 mm. Otherwise the bundles become too heavy, which will result in dangerous situations (during transport & loading/unloading the bundles). This restriction is based on the judgment of Chris van Meeteren.
2. Only a part of Tata Steel Tubes' customer can process bundles consisting of 5 tubes. This restriction is elaborated upon below:

After a second meeting with Chris van Meeteren, it became evident that some customers are unable to process 5 tubes in one bundle. If Tata Steel Tubes would decide to only offer bundles of 5 tubes, some customers and the corresponding profit will be lost. On the other hand, the processing time of the bottleneck would be increased and thus the output rate of the whole chain would increase, which implies an increase in produced tubes per time period. The increased production quantity implies a higher profit. It might seem like you will inevitably loose a part of the potential profit, regardless the decision that is made. However, I propose to identify the customers that cannot process bundles of 5 tubes and inform them on the situation. Two further courses of action are possible:

1. Offer bundles of two tubes only to the customers that are unable to process bundles of 5 tubes. The other customers, will receive the tubes in bundles of 5 tubes.
2. Offer a discount for bundles consisting of 5 tubes or increase the price for bundles consisting of 2 tubes. This will force the customers that are unable to process bundles of 5 tubes to consider the possibility to invest in tools that make them able to process the bundles of 5 tubes.

The solutions above take advantage of the increased profit when the tubes are bundled in bundles of 5 tubes, without losing the customers that are unable to process the bundles of 5 tubes. This is the most beneficial outcome of the evaporation cloud of the increased total tube length per bundle. The EC helped to develop this solution, since it provided an overview of the arguments involved and has limited the solution space to solutions that take the most influential factors (wants) into consideration.

The whole other scenario would be to base the course of action on the highest net profit. So, does the increased profit earned by the increased production quantity outweigh the loss of customers? If so, the tubes should be bundled in bundles of 5 tubes. If not, the tubes should be bundled in bundles of 2 tubes.

5.4 Additional improvement possibility 2

Additional improvement possibility 2 is to increase strapping capacity by adding an extra strapping machine. To decrease the processing time, we can either decrease the cycle time or decrease the number of cycles needed to finish the whole process. This solution will decrease the number of cycles needed. Figure 20 presents the EC corresponding to this situation. An additional strapping machine will cost a lot of money; however, it will also result in a higher production quantity per hour which will lead to an increased profit. To provide more insights in the investment needed, I contacted Tallpack, which is the supplier of the strapping machines. This is discussed in the 'investments' chapter. To determine which of the two needs are invalid considering the goal, the increase in production speed (5 simulation study) and the corresponding increase in profit should be determined. The next step is to determine whether the extra profit because of the extra strapping machine outweighs the cost of the strapping machine. If so, the argument that 'the cost of an extra strapping machine is too high' is invalid, since more profit will be earned.

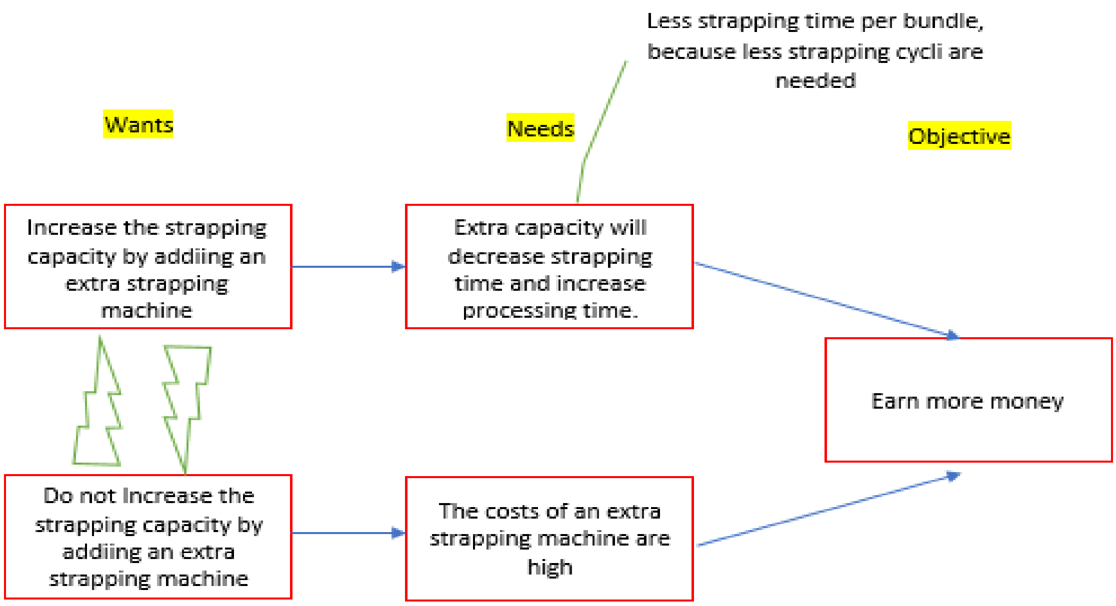


Figure 20: Evaporation cloud of an additional strapping machine

5.5 Additional improvement possibility 3

Additional improvement possibility 3 is to decrease strapping time by decreasing the number of straps needed to strap one bundle by strapping with a stronger strapping material. Fewer straps needed to finish one bundle will decrease the number of cycles needed to finish one bundle, so it will decrease the strapping time. One condition should be met for this solution to be effective; the decrement of straps needed should be an even number, because when the total number of straps needed is uneven the amount of cycles needed to strap one bundle is the same as the total number of straps needed for the uneven number + 1. In case of an uneven number of straps, the strapping machines just strap with one machine in the last cycle, thus the second machine is not utilized. The developed EC for this situation is presented in figure 21.

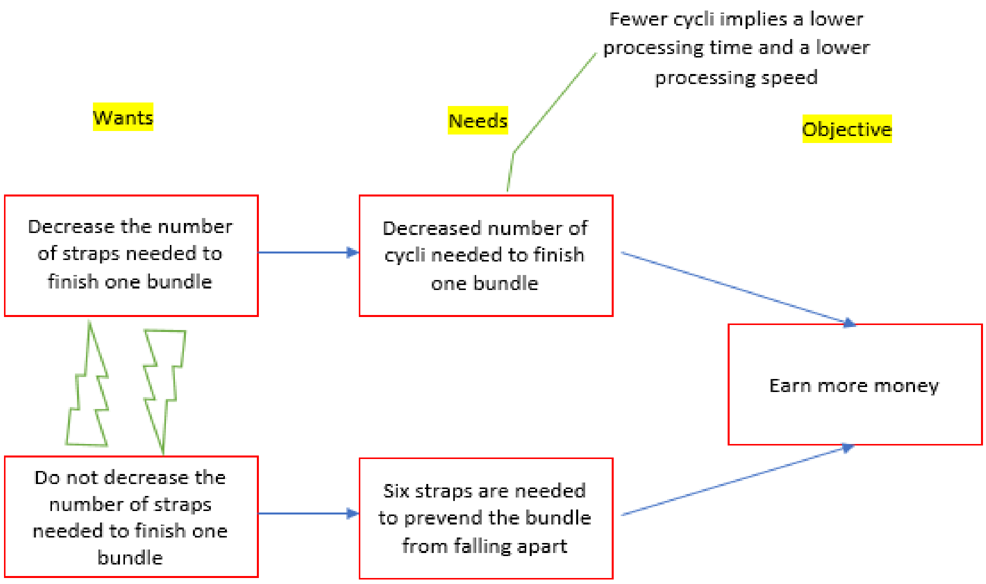


Figure 21: Evaporation cloud of the use of stronger straps

It would be irresponsible to just decrease the number of straps, because the straps serve an important purpose. The straps prevent the bundle from falling apart. If it does fall apart, the safety of anyone near the bundle will be in jeopardy. The tubes easily weigh 600 kg, so if someone is hit by one of those tubes, there will be a health and safety issue. It would be unethical to put the lives of employees in jeopardy and health and safety issues are costly. The number of straps needed is determined by the strength of each strap and the force upon them. Tallpack (the supplier of the straps and machine) has been contacted to gather additional information on this matter:

1. Currently, 6 straps are used to strap one bundle. The straps that are used are 31.75x0.8 MK. The numbers are the strap size in millimetres (width*thickness) and MK represents the strap type. The length of the straps is dependent on the perimeter of the package; in this case the perimeter of the bundle. The break force of the 31.75x0.8 MK is 20320 newtons. The break force is the force that should be placed on the strap for it to break.
2. Tallpack suggested to strap with 31.75x0.8 HT, which is a stronger strap with a break force of 26162 newtons.

At Tata Steel Tubes the force on the straps is determined by the weight of the bundle and by the number of bundles that are stacked on top of each other (the bundle on the bottom of the stack will experience the highest force).

The formula that Tallpack provided to determine the number of straps needed is:

$$Number\ of\ straps\ needed = \frac{Weigth\ product * 1.65}{(\frac{Breakforce * 0.8}{10})} = \frac{Weigth\ product * 16.5}{Breakforce * 0.8}$$

The weight of the product is multiplied with 1.65, because of a safety margin of 65%. The break force is multiplied with 0.8, because the connection mechanism of the straps results in a 20% loss in strength. This formula solely determines the number of straps based on the weight of the package. To incorporate the effect of stacking the bundles on top each other, Tallpack advised to multiply the number of straps needed with the number of bundles that are stacked upon each other. This is an extreme simplification of the actual calculations that are needed to determine the number of straps needed, but Tallpack advised to use this formula.

At Tata Steel Tubes, there are bundles which are strapped with half the number of straps needed based on the formula above. The straps do not break; therefore, I assume that the 'true' number of straps needed is half of the number of straps needed based on the formula above. Furthermore, the number of bundles stacked upon each other is 6, since a stack of 6 bundles is needed to load the transportation truck. The table in appendix B presents the number of straps needed when the switch to stronger straps is made. The values in the table in appendix B have been computed based on the formula and the assumptions. The table shows that all the tubes, except for the 323x10, can be strapped with 4 straps.

The evaporation cloud provided insights in the important factors in the conflict. Based on the analysis, the argument that 6 straps are needed to prevent the bundle from falling apart turns out to be inaccurate, since stronger straps decrease the number of straps needed from 6 to 4 straps.

5.6 Future Reality Tree (FRT)

A future reality tree has been set up (figure 22) to determine the effect of the proposed interventions on the problem based on cause-effect logic. Cause-effect logic can only indicate whether the effect is positive or negative, but it cannot quantify the degree of positivity or

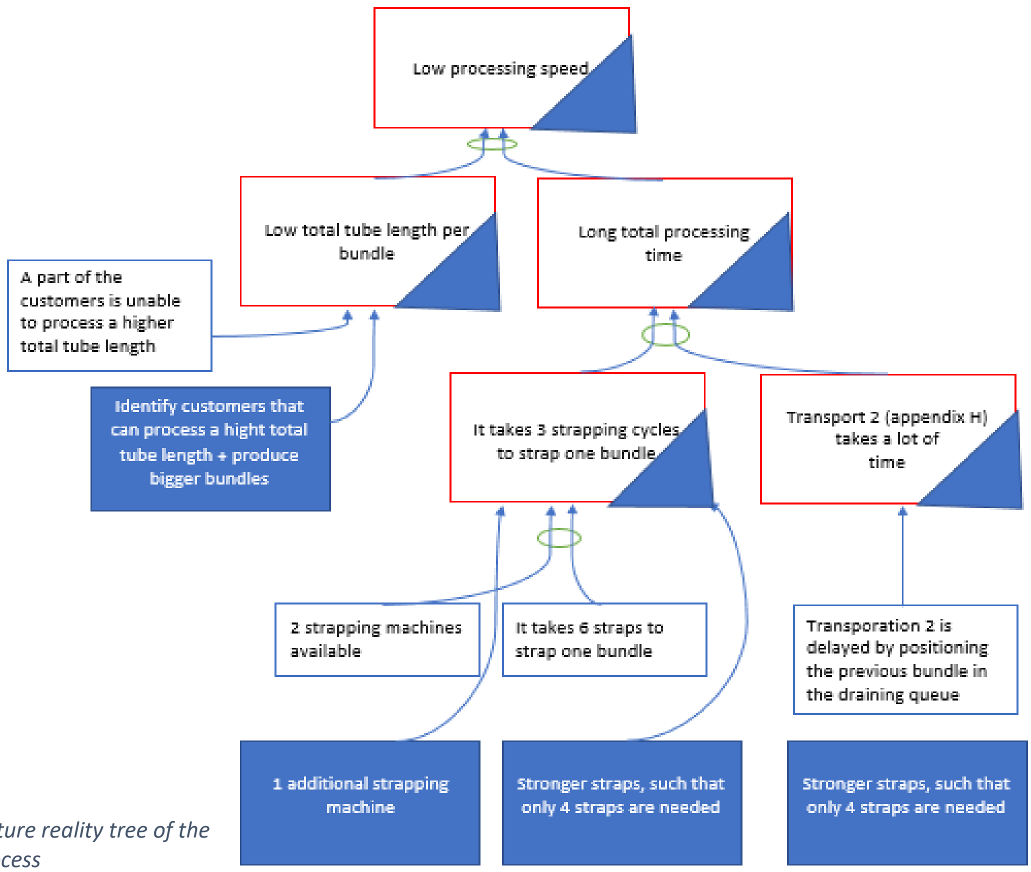


Figure 22: Future reality tree of the strapping process

negativity. The blue triangles in the right corners of the undesired effects indicate that the solutions (blue rectangles) have a positive effect on the undesired effects.

6 Simulation study

A simulation model has been developed in Plant Simulation to evaluate effectiveness regarding speed increasement of the proposed interventions.

6.1 The model in general

Current reality

Figure 23 contains a basic flowchart of the simulation model. The model starts by sending the tubes through the tube mill. The tube mill will process the tubes with a particular speed in meters/minute. The station 'tube mill' in the plant simulation model looks up the processing time in a table. It checks the tube that comes in and automatically sets the appropriate processing time, since the processing time is tube dependent. The next step is to enter the conveyor belt to the MAIR. The conveyor belt has a capacity of 60 tubes and the speed of the conveyor belt is 0.5 meter per second. If the conveyor belt reaches its capacity, the tube mill is stopped until the conveyor belt is empty again. The processing time of the MAIR is bundle shape dependent, which is dependent on the amount of tubes per bundle. The MAIR checks the required tubes per bundle and sets the processing speed accordingly. If there is no tube in the strapping machine, the MAIR can send the bundle of tubes to

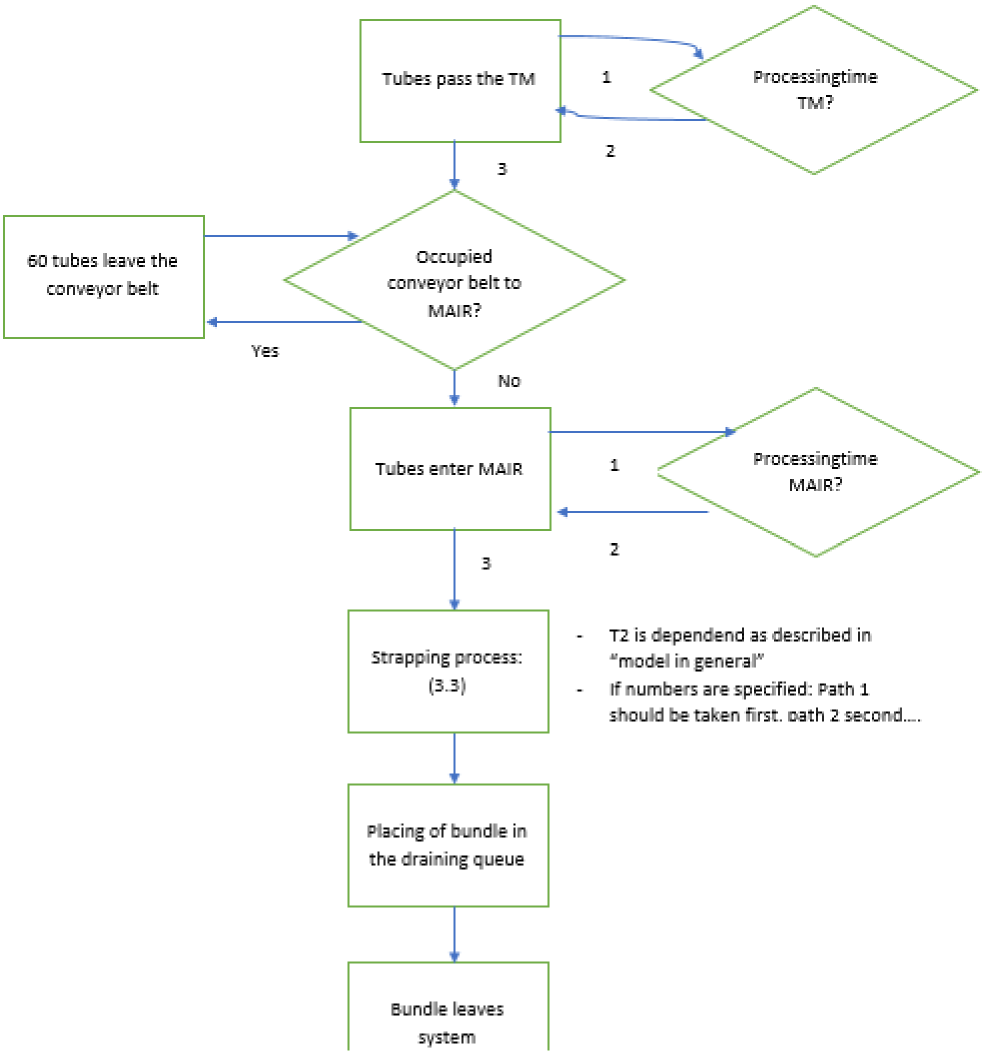


Figure 23: Basic flowchart of the steps taken in the simulation model

the strapping machine, else the bundle must wait in the MAIR. In the second case, the moment that the bundle leaves the strapping machine, the model checks whether there is a bundle waiting in the MAIR or not; if so, the bundle is moved into the strapping machine. Depending on the straps needed to strap a bundle, the model determines how many strapping cycles the bundle must go through and the distance between the straps. As described earlier, "Transport 2" (figure 15) is dependent on placing the previously strapped bundle into the draining queue. The model takes this into account, because the strapping cycle after "Transport 2" can only start, if the placing of the bundle into the draining queue has been finished. After the strapping, the bundle is transported to and placed in the draining queue. Finally, the bundle leaves the system

Experimentation – future reality
In the experimentation, the KPIs as described in 5.3 are analysed. Each experiment differs in independent input variable and the change in the KPIs are analysed. The independent input variables are described in 5.2. Appendix C shows the values of the independent variables per experiment. In total 8 experiments will be conducted. 1 experiment will evaluate the current reality, 4 experiments will evaluate the effectiveness of the interventions on their own and the remaining 3 experiments will combine the decreased hinder of the downstream process with each of the additional improvement possibilities (4 solution generation).

6.2 Input:

Constant input

- Tube mill processing time per tube: appendix A
- Processing time MAIR: number of tubes per bundle dependent (2 tubes inn a bundle: 25 secs; 5 in a bundle: 50 sec)
- Appendix D

The independent variables.

- Number of straps needed to finish one bundle: 4 or 6
- Number of tubes in one bundle (increase total tube length per bundle): 2 or 5
- Number of strapping machines: 2 or 3
- 25% increase in processing time of the subsequent downstream process, which leads to a decreased hinder of the strapping process): True or False

6.3 Output:

The output KPIs will be:

- processing speed of the Tube Mill
- Processing speed of the strapping process
- System's output speed
- The fraction of the time that the tube mill is stalled (fully occupied conveyor belt MAIR)

The processing time of the Tube Mill and the processing time of the strapping process allows us to compare the two. The system's output speed allows us to evaluate the production speed of the chain. The fraction of the time that the tube mill is stalled indicates the unused potential of the tube mill.

6.4 Assumptions

The product flow, relationships between events and dependencies as described in 5.1 are assumed to be the realistic. Some additional assumptions have been made to create an accurate representation of the M-93:

Input assumptions:

- Tubes move with a speed of 0.5 meters per second on the MAIR conveyor belt. (Based on: Clement Blacquiere)
- Processing time of the tube mill: appendix A (based on: already existing data & interview with Eric van de Steen)
- Processing time of the strapping machine is 10 seconds (based on sampling: figure 15 & 16).
- Processing time of filling the strapping machine is 5 seconds (based on sampling: figure 15 & 16)
- The queue in front of the MAIR can store 60 tubes: (273mm + 323 mm)/2 ≈ 300 mm; 18000/300 = 60 tubes
- In the strapping process the bundle moves with a speed of 0.75 meter of tube per minute (based on: (1) sampling: figure 15 & 16 (2) Clement Blacquiere)
- Strapping: I assumed that the first pair of straps is placed 75 cm from the edge of the bundle and the length between the strapping machines equals 2.5 meter when 4 and 6 straps are needed to strap one bundle and 2 meters when 3 strapping machines are used. The distance between the strapped pairs is dependent on the scenario that is being evaluated. We distinguish the following scenarios:
    - <u>number of straps needed is 4:</u> the distance between a pair of straps 5.5 meter (Transport 2 (T2) = 4; T2Addtion = 4; T1 = 4).
    - <u>Number of straps needed is 6:</u> the distance between a pair of straps is 1.5 (T2 = T1 = T3 = 4; T2Addition = 0;) meter.
    - <u>straps needed & 3 strapping machines:</u> Length between straps is 2 meters. So, the distance between the combinations of three straps is 2.5 meter. (T2 = 4m; T1 = 5.5m; T2Addition = 2.5)

      *Note: the distances above are based on the assumptions described above the enumeration and the assumption that the straps are divided symmetrically over the bundle.

Solution assumptions:

(1) <u>Increased total tube length</u>: the whole situation stays the same, except for the amount of tubes that is bundled.

(2) <u>One additional strapping machine</u>: The extra strapping machine is placed in front of the existing strapping machines. 6 straps are needed to strap the bundle. 3 straps are strapped per cycle.

(3) Stronger strapping material: 4 straps are needed instead of 6. Two straps are strapped per cycle, which results in 2 strapping cycles instead of 3.

(4) The processing time reduction of placing the previously strapped bundle in the draining queue is 25%.

*Note: Assumption 2 and 3 both result in one less strapping cycles, however this result is achieved by different means. The strapping process is modelled as described by the logic in (3.3). In the scenario of assumption 2, we strap 3 straps at the same time instead of 2. In the scenario of assumption 3, the TSN reduces. The distances between the straps affect Transport 1,2 and 3 (T1, T2 and T3; figure 15)

6.5 Simplifications

- The simulation model is a detailed model of the strapping process. This model is detailed, yet simplified in the way that the other workstations in the production line are not presented in the model. This will not have any negative effects, since the model serves as a mode to evaluate whether the processing speed of the strapping process is increased such that it meets the processing speed of the tube mill and the excluded workstations do not affect the strapping speed.

- The model does not consider machine failure. I choose this approach, because there is no data of the machine failures. I did not want to use an estimate of the probability of machine failure because it would be too inaccurate and its impact of the estimation would be too big.
- I have simplified the process of placing the previously strapped bundle in the draining queue. It has been modelled as one process, however in reality several steps take place, but since the total processing time of the process is the influencing factor, this simplification will not result in invalid output.
- The tube mill does not slow down when the queue in front of the MAIR tends to become fully occupied. In practise this is the case.
- At the end of 'Transport 2' (T2: figure 15), the model checks whether the process of placing of the previous bundle in the draining queue has been finished. This feature imitates the hinderance of placing the previous bundle in the draining queue. In reality, the hinderance might occur somewhere during T2, but this difference between the reality and the model will not impact the output. It will not even impact the scenarios in which the strapping distance differs, because the additional strapping difference is modelled with line 'T2Addition' and line 'T2' still has the same length as in the current reality scenario.

6.6 Technical details of the model

Plant Simulation has been used to set up the simulation model. Plant Simulation combines input variables and programming to imitate a real-life situation and if programmed, it can measure certain KPIs. In Plant Simulation, the code is referred to as 'methods'. I will refer to the code in the same way.

The model consists of two frames. The 'rootframe' and an additional frame 'bundelen'. The rootframe (appendix e) is the frame of the production line. The frame 'bundelen' (appendix e) is a subframe which exists within the rootframe. The rootframe represents the whole production line and the subframe 'bundelen' represents the bundling process. For the simulation to run, input must be specified (in this scenario as described above), the flow and logic must be set by methods and output measures must be computed and stored. The frames (appendix e) show the stations, which the (intermediate)product passes. All those stations represent a step in the production line. Furthermore, input variables and input tables have been used to set the input as specified above (appendix e – figure 24 below 'input'). Also, below the heading 'output' the information needed to compute the KPIs and the KPIs themselves are stored. Below an explanation of the important methods is presented.

Stall the tube mill (appendix e)
This method is called with the use of an observer. An observer observes a by plant simulation specified variable and when the variable's value changes it executes a certain code. In this case, the variable 'NumMu' of the object 'line' is observed, which implies that the number of products on the conveyor belt is being observed. Each time that this number changes, the code (appendix e) will be executed. The production line must be stalled only if the total capacity of the conveyor belt has been reached and it must be started again if the number of tubes on the conveyor belt equals 0. The station can be stopped and started again with the build-in method 'failed'. If 'failed' has been set true or false, the station will either be stopped or started. In the method an if-then statement is used.

Flow/movement
The method 'Move1' sets the product movement in between the stations. The movement is dependent on the scenario that is simulated. This paragraph will shortly describe the main features of the 'move1' method and the paragraphs below will describe the differences in movement for the scenario depended ''moves'. The method 'Move1' is executed when the objects 'MAIR' and 'Cyclus 1' are finished. When the method is called when the MAIR has finished, the next move is dependent

on whether the strapping process is occupied or not (appendix e). The MAIR checks the Boolean variable 'BundleInStrapping' if its value is 'false' the bundle can enter the strapping process, if its value is 'true' it cannot enter the strapping process and the Boolean variable 'TubeWaitingMAIR' is set to 'true' (appendix e).

Additional strapping machine
In the 'Cyclus 1 logic' and 'MAIR logic' methods, the 'NumberOfStrappingMachines' variable is used. This variable is one of independent input variables. When the bundle enters the strapping process, the total number of straps needed is looked up in one of the input tables. When the code is executed for the first time (at the end of the MAIR), the total number of straps needed is placed in a table which logs all the bundles in the system. Each time the code is executed from that point on, which equals the number times that the bundle passes the station 'cyclus 1', the 'NumberOfStrappingMachines' is subtracted from the 'total number of straps needed' in the logging table. Based on this new value 'total number of straps needed', it is determined whether the bundle must pass the 'Cyclus1' station for another time or not. For future, studies I have added the feature to send the bundle to a station which straps less straps than the total number of strapping machines available.

Stronger straps
The independent variable 'StrapsNeeded' is placed in the input table. The number of straps needed could be set as tube dependent input, but this is unnecessary for this research. From that point on, the flow as described in 'additional strapping machine' is followed. It should be clear that the solution of using a stronger strapping material, which implies less straps needed, can be simulated with this feature.

More tubes per bundle
The number of tubes per bundle is determined at the MAIR, because that is where the bundle shape is created. A bundle of 5 tubes consists of 2 layers, so the total processing time of the MAIR must be set to 2 * 25 = 50 seconds. The method 'EntranceMAIR' (appendix e) makes sure that the processing time is set appropriately depending on the value of the variable 'TubesPerBundle'. The method 'EntranceMAIR' is executed when the tubes enter the MAIR. The MAIR has been modelled with an 'assembly' object, which implies that the assembly list has to be set. The assembly list determines how many tubes enter the MAIR and therefore it determines the number of tubes in a bundle. The method 'SetAssemblyList' (appendix e) is executed when the 'container' object leaves the source to the MAIR and creates the assembly list of the MAIR depending on the value of the variable 'TubesPerBundle'.

Check tube MAIR
When the 'MAIR Logic' method has been executed, it will not be executed another time. This becomes a problem, when there was a bundle in the strapping machine and therefore the bundle in the MAIR could not be moved. It would stay there, till the end of the simulation and it would stall the rest of the production line. This is realistic, but will not happen in reality, so an extra method was needed which checked whether there was a bundle waiting in the MAIR or not and move it to the strapping process at the right time. The right time is at the end of the strapping process, so after 'transport 4' in figure 13 and after 'transport to draining queue' in the simulation model. This is modelled with another observer on the line 'TransportToDrainigQueue' (appendix e). Again, the variable NumMu is observed. If NumMu has a value 0 and the old value was 1, which implies that a bundle leaves the line, the condition in the if-statement is true and the code is executed. The first code that is executed is a check-up on whether the strapping process is occupied or not. If not, and the variable 'TubeWaitingMAIR' has the value 'true' all the necessary logging info is stored and the bundle is moved to the strapping process.

Hinderance of placing the previous bundle in the draining queue
The hinderance of placing the previously strapped bundle in the draining queue has been programmed with a 'waituntill' function. When such a function is encountered in a method, the simulation progresses, but the code is not executed any further until the statement in the function becomes 'true'. In this case, when the station 'PlacingBundleInDrainingQueue' is not occupied anymore. When the station 'PlacingBundleInDrainingQueue' is not occupied anymore, the bundle in the strapping process can progress (appendix e).

KPIs
The output measures must be computed via methods. Appendix e contains the method for the KPI computations. The KPI method is called at the end of the simulation when the bundle leaves the system. The output speed, the strapping speed and the fraction of the time that the tube mill is stalled are computed using basic and logical calculations. After, these measures are stored in the table 'exp1'.

6.7 Model Verification
Verification is the process of ensuring that the conceptual model has been transformed into a computer model with sufficient accuracy (Ronbinson, 2004).

The criteria for the logic, product flow and dependencies between events are described in 5.1. Based on my judgement, the computer model that is developed in plant simulation exactly meets those criteria. In the 5.9 the output data is explained, which verifies the model as well. Also, the output speed equals the processing speed of the bottleneck in every situation. This is what is expected based on TOC.

6.8 Model validation
Sanne Kramer evaluated the input assumptions, output assumption and reasoning on which the simulation model is based and found those to be valid enough considering the purpose of the study. This implies that if the model is working according to criteria set out by the input assumptions, output assumptions and reasoning, we can conclude that the model is valid. This check will be performed in 5.9.

6.9 Output verification & analysis
The experiments have been described in 'The model in general'. This section will analyse the output of the simulation model when running the 8 experiments. Run length: 48 hours; Warm-up period: 200 bundles. The data points in the warm-up period have been excluded with the use of excel. Appendix C shows the values of the independent variables per experiment. The warm-up period has been set to 200 bundles, because after 200 bundles, the output speed becomes steady (steady-state has been reached). The run length has been set to 48 hours, to get accurate results, while considering the time it takes to run all the experiments. It should be noted that the warm-up period and run length are more important when running a simulation model consisting of many stochastic processes compared to a model consisting of constant processes (model developed for this thesis). However, even in the developed model of the M-93, the warm-up period still serves the purpose of preventing the output to be affected by initial-bias.

The output tables are presented in appendix F. Below you can find an explanation of the output data, which verifies the model

Current reality
In the scenarios where the strapping process is the bottleneck (the wall thickness of the tubes is lower than 10 mm). The processing speed of the strapping process is approximately 21 meters per minute in the current reality. This is what was expected, based on figure 15 and 16. If the tube mill is

the constraining factor of the output speed, the strapping speed increases. This is a logical consequence, because the process of placing the bundle of tubes in the draining queue is only constraining the strapping speed, when the bundles leave the strapping process with an inter departure time which approaches 0 (subsequent bundles follow each other closely). This only is the case when the strapping process is the bottleneck. This characteristic is reflected in the output of all the experiments below and therefore this will not be mentioned for each experiment. The tube mill is stalled less frequently when the processing speed of tube mill decreases. This makes perfect sense, since the input speed of the conveyor belt to the MAIR decreases, which implies that it takes more time until the conveyor belt is fully occupied.

Experiment 1
The experiment has been run for a part of the tubes, because it is impossible to increase the tubes per bundle for the other tubes (4.3). The strapping speed equals 70.6 meter per minute. This increase has been achieved by increasing the number of tubes per bundle from 2 to 5. The total tube length per bundles is increased by 150%. Furthermore, the processing time is decreased to 51 seconds per bundle, because the bundle is not hindered by the process of placing the bundle in the draining queue (calculation: appendix G). The new processing time and increased number of tubes per bundle results in an expected speed of 70.6 meter of tube per minute, which equals the output of the simulation model. The fraction of the time that the tube mill is stalled is 0%, because the strapping process is not the bottleneck for the production of any of the tubes.

Experiment 2
The 323 with wall thickness 10 and 12.5 have been excluded from this experiment, because those tubes are too heavy for this solution (4.5). The strapping speed is 23.9 meter per minute. This is an increase of 17% compared to the current reality. This increase has been achieved by reducing the strapping time. One less strapping cycle is needed to strap the bundle (solution assumptions). This reduces the total strapping time with 10 seconds. The total strapping time is approximately 70 seconds. 70 seconds – 10 seconds = 60 seconds. In those 60 seconds, 24 meters of tube is being processed. This leads to a processing speed of (24/60) *60 = 24 meter of tube per minute. This validates the strapping speed of experiment 2. Also, the fraction of the time that the tube mill is stalled is decreased compared to the current reality, which is a reasonable consequence of increasing the output speed of the MAIR conveyor belt (higher strapping speed).

Experiment 3
The same reasoning as for experiment 2 applies. Even though, the solution assumptions or experiment setups are not completely the same, the effect of the interventions are; both the interventions result in one less strapping cyclus. If the output data of experiment 2 and 3 would differ, we could already state that the model had to be invalid.

Experiment 4
Strapping time is reduced with 10 seconds, since the time that the strapping process is hindered is reduced with 25%. A more thorough explanation can be found in 4.2. The total strapping time reduces to 60 seconds. In those 60 seconds, 24 meters of tube is processed. This results in a speed of 24 meter of tube per minute, which approximately equals the strapping speed of the simulation output: 23.9 meter of tube per minute.

Experiment 5
The experiment has been run for a part of the tubes, because it is impossible to increase the tubes per bundle for the other tubes (4.3). The results of experiment 5 are the same as the results of experiment 1. This was expected, because in experiment 1, the bundle in the strapping process did not experience any hinder of the process of placing a bundle of tubes in the draining queue. So,

decreasing the processing time of placing a bundle in the draining queue does not have any positive or negative consequences on the total strapping time.

Experiment 6
The 323 with wall thickness 10 and 12.5 have been excluded from this experiment, because those tubes are too heavy for this solution (4.5). The combination of one less strapping cycle in combination with an increased processing speed of placing the previously strapped bundle in the draining queue results in a strapping speed of 28.6 meter of tube per minute. One less strapping cycle and a decrease of 25% in processing time (placing bundle in draining queue) results in a decrease in strapping time of 20 seconds. The strapping time becomes 50 seconds. In those 50 seconds, 24 meters of tubes is being processed. The processing speed expected is (24/50) *60 = 28,8 meter of tube. This validates strapping speed output of experiment 6.

Experiment 7
The same reasoning as for experiment 6 holds.

6.9.1 Differing experiment setups & the same output:

Experiment 1&5: Both the output of experiment 1 and 5 are the same. This is the case, because the only different factor between the two experiments is the increase in processing speed of the process of placing a bundle of tubes in the draining queue; in experiment 1, the processing speed is not increased and in experiment 5 the processing speed is increased. The results are the same, because in experiment 1, the bundle that is being strapped is not hindered by placing the previous bundle in the draining queue. The time hindered = 0. The decrease in strapping time by increasing the processing speed of placing one bundle in the draining queue, is based on the fact that hinderance exists and that the increased processing speed of placing one bundle in the draining queue, decreases the time hindered. Since the time hindered already is 0, we cannot decrease the time hindered and therefore the output of experiment 1 and 5 are the same.

experiment 2&3: Already explained in 'experiment 3'

Experiment 2&3&4: Since it has already been explained why the output of experiment 2 and 3 are equal (5.9), the only thing left to explain is why the output of experiment 4 equals the output of experiment 2 & 3. In experiment 4, the processing time of placing the previously strapped bundle in the draining queue (40 sec) is decreased with 25%. 25% of 40 seconds equals 10 seconds. Those 10 seconds are subtracted from the time hindered, which equals 16 seconds. The strapping time reduces with 10 seconds. It is a coincidence that this reduction of 10 seconds equals the reduction of 10 seconds because of one less strapping cycle in experiment 2 and 3.

experiment: 6&7: The total distance before the end of Transport 2 (T2: figure 15) is the same in both the experiments and therefore the total time that the bundles are hindered by placing the previous bundle in the draining queue is the same. Therefore, both the experiments are affected the same way by reducing the total time hindered because of increasing the processing speed of placing a bundle in the draining queue.

6.9.2 Cross-case analysis

Appendix H presents a table of a cross-case analysis of the strapping speed of the current reality and experiment 1, 4, 6 and 7. Experiment 2 and 3 have been excluded, because it would not be recommendable to implement any additional improvement possibilities without first decreasing the hinder time of placing the previously strapped bundle in the draining queue. Experiment 5 has been excluded, because the strapping process is not hindered by placing the previously strapped bundle in the draining queue in experiment 1 and therefore the results are the same as in experiment 1. The black blocks represent scenarios that are not possible due to the restrictions that are described in '4 solution generation'.

Increasing the number of tubes per bundle from 2 to 5 tubes increases the processing speed from 20.5 to 70.6, unfortunately this is only possible for a part of the tubes, due to the increased weight per bundle. Combining the increased processing speed of placing the previously strapped bundle in the draining queue with an additional strapping machine or stronger strapping material results in an increase in strapping speed from 20.5 to 28.6. Solely, increasing the processing speed of placing the previously strapped bundle in the draining queue, results in an increase in strapping speed of 20.5 to 23.9.

6.10 Intermediate conclusion: answer to RQ2

What interventions can eliminate the cause of the underperformance on the speed at which the tubes arrive in the outside storage of the M-93 at Tata Steel Tubes?

The strapping speed is affected by two factors: the total meter of tube per bundle and the time it takes to strap the bundle. Four possible interventions that affect these two factors have been determined:

(1) Increase the processing speed of placing the previously strapped bundle in the draining queue, to decrease the time that the strapping process is hindered.
(2) Increase the number of tubes per bundle from 2 to 5 tubes.
(3) Increase the number of strapping machines from 2 to 3 machines.
(4) Decrease the number of straps needed from 6 to 4 by using a stronger strapping material.

The goal of the research is to increase the processing speed of the strapping process, such that it meets the speed of the tube mill. Figure 24 shows the improvement regarding the goal. The future reality is the scenario of (1) 5 tubes per bundle, when applicable (2) Increased processing speed of process downstream of strapping to decrease the experienced hinder (3) stronger strapping material or an extra strapping machine.

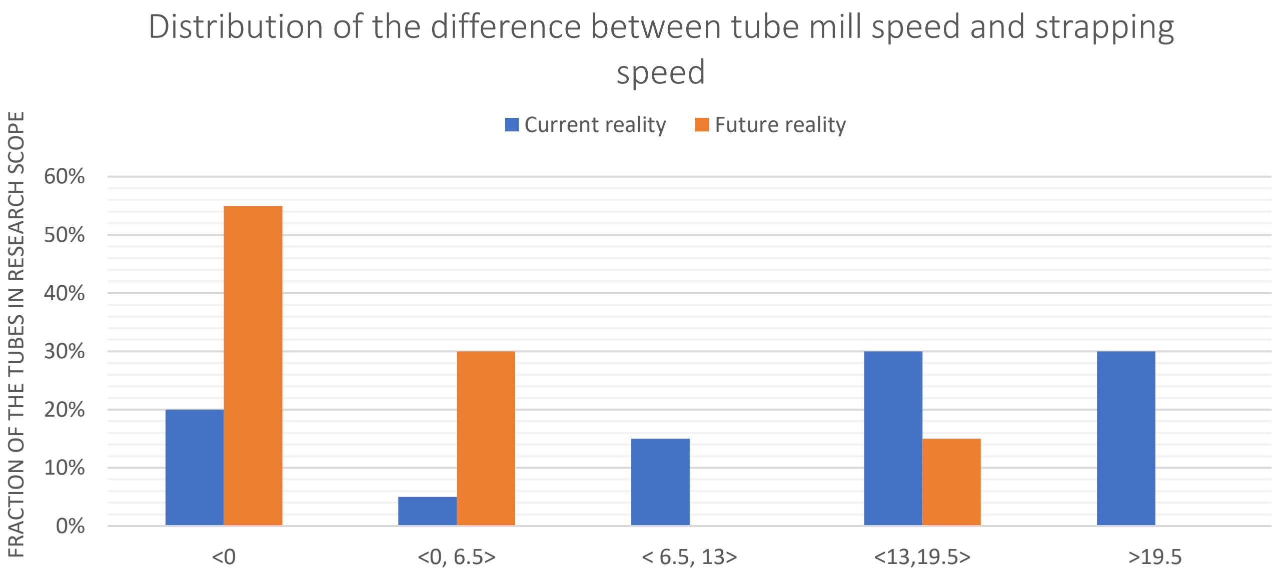


Figure 24: Distribution of the difference between tube mill speed and strapping speed

Based on figure 24, we can conclude that the goal has not been met for all the tubes in the research scope, however we see significant improvement. In the future reality, the difference between the tube mill speed and strapping speed is lower than 6.5 meter per minute for 85% of the tubes. In the current reality this is only true for 25% of the tubes. In the future reality, the center of mass of the distribution has moved to the positive side drastically.

These results have been achieved, by implementing the following interventions:

1. increasing the number of tubes per bundle from 2 to 5 tubes per bundle for the tubes with a wall thickness upto 5 mm increases the strapping speed from 20.5 meter per minute to 70.6 meter per minute.
2. A combination of increasing the processing speed of placing the previously strapped bundle with an extra strapping machine or stronger straps increases the strapping speed from 20.5 meter per minute to 28.6 meter per minute.

7 Investments

In the previous sections, several improvement possibilities have been proposed to increase the speed of the strapping process. Since, the strapping process is the bottleneck of the M-93, when producing the 323 and 273. This section provides insights in the necessary investments.

Increased processing speed of placing a bundle in the draining queue
Further research is required to determine the investment required of implementing this solution. The research should point out the technical aspects of the improvement. This is out of scope for this bachelor thesis. Also, further research should point out whether it is needed to split up the transportation sections and use a pulse counter in combination or if solely implementing one of those improvements will be sufficient.

More tubes per bundle
The investment required to increase the number of tubes per bundle from 2 to 5 is 0 euros. The input values of the MAIR must be adjusted and the improvement is implemented. The improvement increases the strapping speed with 250% for a part of the tubes, which is an amazing result for an investment of 0 euros. ‘

Additional strapping machine
Tallpack is the company that supplied the strapping machine at Tata Steel Tubes. The representative came to the site to inspect the possibility of adding an extra strapping machine. An extra strapping machine will cost Tata Steel Tubes 200.000 euros. Additionally, a 10% installation fee must be paid, so the total investment will be 220.000 euros.

Stronger strapping material
Switching from the 31.75x0.8 MK strapping material to the 31.75x0.8 HT implies an increased break force of approximately 30%. The MK strapping material costs 1097.88 euros per 1000KG. The HT strapping material costs 1222.08 euros. The relative increase in price is approximately 11% and for a part of the tubes in the scope of this research, the number of straps needed to finish 1 bundle decreases with 33%. This implies that money could be saved by switching from the MK to the HT strapping material. Further research should be conducted to determine the decrease in straps needed for the bundles of tubes that are outside of this research scope. Also, a decision should be made on whether it would be beneficial to switch between strapping material during the production runs.

8 Conclusion

The bottleneck of the M-93, when producing the 323 and 273, is the strapping process. The processing speed of the strapping process is 21 meters per minute. Currently, all the other workstations of the M-93 have a higher processing speed. The low processing speed is caused by a relatively long processing time in combination with a low number of tubes that is processed in this timeframe. Two causes of the long processing time have been identified:

1. The strapping process is hindered by the process downstream in the production line.
2. The strapping process takes 3 strapping cycles, which takes a relatively long time.

The low number of tubes per bundle is an unnecessary evil when producing a part of the tubes in this research scope. For the 323 and 273 with a wall thickness up to 5 mm, the tubes per bundle could be increased to 5 tubes per bundle. The tubes with a higher wall thickness cannot be bundled with 5 tubes per bundle, because the bundles will become too heavy. The following improvement possibilities have been proposed:

1. Decrease the strapping time, by decreasing the time the strapping process is hindered. This can be achieved by increasing the processing speed of placing the previously strapped bundle in the draining queue. The processing speed can be increased by splitting up the transportation process in two sections: one for the strapping process and one for the transport to the draining queue. Additionally, the processing speed could be increased by investing in a more accurate pulse counter for the horizontal transport to the draining queue.
2. Increase the number of tubes per bundle to 5 tubes for the 323 and 273 with a wall thickness up to 5mm.
3. Decrease the strapping time by switching to a stronger strapping material to reduce the number of straps needed to finish one bundle from 6 to 4, which implies one less strapping cycle.
4. Decrease the strapping time by increasing the strapping capacity with an extra strapping machine which implies that one less strapping cycle is needed to strap one bundle.

Improvement 1 increases the strapping speed with 17% to 23.9 meters per minute. Improvement 2 increases the strapping speed with 250% to 70.3 meters per minute. Improvement 3 and 4 both have the same outcome (one less strapping cycle), which results in an increase in strapping speed of 17% to 23.9 meters per minute. Improvement 1 in combination with improvement 3 or 4 increases the strapping speed with 40% to 28.6 meters per minute.

The goal was to increase the processing speed of the bottleneck such that it would meet the processing speed of the tube mill. This has been partly achieved as can been seen in figure 24. The goal has been achieved for 55% of the tubes in the research scope and for 85% of the tubes in the research scope the difference between tube mill speed and strapping speed is lower than 6.5 meter per minute.

9 Discussion

Added value of TOC
The theoretical framework of scientific research provides a starting point to conduct your own research. The theory of constraints proved to be a valuable starting point for my research. It created structure in the chaotic world of production process research and optimization. For starters, reading the goal (Goldratt, 2004) improved my understanding of process optimization methodology. I used this methodology throughout my own research. The bottleneck has been identified, it was already exploited and my research created possible elevation solutions. The paragraph below goes into the 'missing' subordination phase. Additionally, the thinking processes were valuable tools to increase the quality of my research. The current reality tree has limited the solution scope to the root causes of the problem in a very efficient and fast way, besides it made the problem analysis easier. The evaporation clouds paved the way to the improvement possibilities. They structured my reasoning, which automatically pointed to effective interventions. The future reality tree served as a check-up on whether my reasoning was indeed, as logical as I thought it was.

Missing subordination phase of TOC
The Theory of Constraints introduces Drum-Buffer-Rope to subordinate all the workstations in the system to the bottleneck, to ensure that inventory is minimalized and operation expenses are reduced to the absolute minimum. This paper did not go into these topics, because the focus was to increase the processing speed and therefore the subordination of the other workstations to the strapping process was less of a priority considering the time restriction that this research was subject to. However, when the desired production situation is achieved, I would advise Tata Steel Tubes to invest some effort to subordinate the line accordingly, because it will save money.

Criticism on TOC
Although, Mahesh, Gupta and Boyd (2008) and Naor, Bernardes and Coman (2012) argue that TOC is a valid theory, they argue that it is still under development as well. Mahesh, Gupta and Boyd argue that TOC still must be empirically tested more often. Mabin (2003) already went in the right direction doing so. Second, they argue that the impact of TOC should be tested in other functional areas such as accounting and marketing.

Value of the research for Tata Steel
- Great and thorough insights in the causes of the problem. Especially, the fact that the downstream process hinders the strapping process.
- Indicate potential improvement possibilities by providing answers to: (1) How to decrease the hinder of the downstream process in the strapping process? (2) Can we reduce the number of strapping cycles it takes to strap one bundle?
- This thesis proposes the out of the box possibility of strapping with stronger straps to reduce the number of straps to strap one bundle. Initially, my colleagues were sceptical about this intervention. After my full proposal and argumentation, they were pleasantly surprised.
- The simulation study and problem analysis provide argumentation in favour of change and they can support an investment proposal.

Insights from discussion meetings with Tata Steel tubes' employees
- The insights on how the downstream process relative to the strapping process hinders the strapping process are very useful.
- It would be best to increase the number of tubes from 2 to 5, because it will solve all the problems

- The assumption that Chris can always decide to increase the transport capacity by adding one of his own trucks might not always be valid, however the buffer capacity will be sufficient to solve this problem.
- It is insightful to know that the Tata Steel Truck on its own does not have enough capacity to process the output of the 323 and 273. In the future, the truck will have an even lower availability to serve the M-93, because it will have to process the output of even more operations.

Solution implementation implications
The solution of an extra strapping machine might pose some difficulties to implement, because extra space needs to be created.

Data gathering methods
During this study, most of the data has been gathered through interviews. An interview is not the most objective data gathering method, but this data gathering method has been chosen, because of time restrictions in combination with the lack of better alternatives. However, most of the time I used an alternative data gathering method like sampling or the gathering of In-line processing data to compare the data that has been gathered through interviews and validate information.

Sampling-Simulation input
In figure 13 'T3' takes approximately 3 seconds. In the model (current reality) T3 takes 5.33 seconds. This decision has been made, because the distance that must be covered is 4 meters. Covering 4 meter in 3 seconds seemed unrealistic.

The simulation model:
Production line modelling has far more possibilities than this study has shown. The model that is used, basically sums up constant time intervals. Which was sufficient to achieve the purpose of this study, regarding its limitations. The limitations of the simulation study were (1) the focussed research scope (2) the lack of historical data. The combination of a very focussed research scope (just the strapping process) and the simulation study might not have been perfect, since simulation modelling will become more beneficial when the process that is modelled gets bigger and more complex. The lack of historical data prevented the use of stochastic events and validation based on historical data. However, the research (as a whole) also benefited from the simulation study, because the development of the simulation model, required me to thoroughly think about the process that was modelled. In this case, this resulted in a lot of additional insights on the relations between influencing factors and the strapping process. Furthermore, in the future, the simulation model could be extended with all the additional workstations in the line. This will make future production line analysis easier (more on this topic in 'future studies').

Future studies
Concerning further studies to process performance of the M-93, it would benefit Tata Steel Tubes if they would invest in an automated measuring system to measure machine-failures, utilization of machinery, the processing speed of each workstation in the production line, setup times, recovery times. If this information is available, the analysis of the production line will be more accurate, which allows to gather even more information and insights about the M-93. This information will improve the decision-making process for future investments.

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11 Appendix

11.1 Appendix A

Table 3: Tube mill's maximum speed. Based on Tata Steel Tubes' in-line measurement data, which has been validated with the use of an interview with Eric van de Steen

Diameter	Wall thickness	Tube mill's speed in m/m
273	4	50
273	4.5	50
273	5	50
273	5.6	45
273	6	45
273	6.3	45
273	7.1	30
273	8	30
273	10	20
273	12.5	20
323	4	35
323	4.5	35
323	5	35
323	6	35
323	6.3	35
323	7.1	35
323	8	30
323	8.8	25
323	10	20
323	12.5	20

11.2 Appendix B

Table 4: Number of straps needed when stronger straps are used

Diameter	Wall thickness	Number of straps needed
323	4	1.79
323	4.5	2.01
323	5	2.23

323	6.3	2.80
323	7.1	3.15
323	8	3.54
323	10	4.39
273	4	1.50
273	4.5	1.69
273	5	1.87
273	5.6	2.09
273	6.3	2.35
273	7.1	2.65
273	8	2.97
273	10	3.68

11.3 Appendix C

Table 5: Experimentation setup

Variable	Current reality	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Total tube length per bundle	24	60	24	24	24
Straps needed to strap one bundle	6	6	4	6	6
Strapping machines	2	2	2	3	2
Decreased hinder of the downstream process	F	F	F	F	T

Variable	Experiment 5	Experiment 6	Experiment 7
Total tube length per bundle	60	24	24
Straps needed to strap one bundle	6	4	6
Strapping machines	2	2	3
Decreased hinder of the downstream process	T	T	T

11.4 Appendix D

Table 6: Input variables simulation

Length conveyor belt MAIR	18M

Conveyor belt MAIR speed	0.5 M/sec
Processing time strapping cycle	10 sec
Processing time filling one strapping machine	5 sec
Conveyor bel strapping speed	0.75 m/sec
Length Transport to draining queue	3.75m
Processing speed: placing previously strapped bundle in draining queue	40s
Tubes per bundle	2

11.5 Appendix E

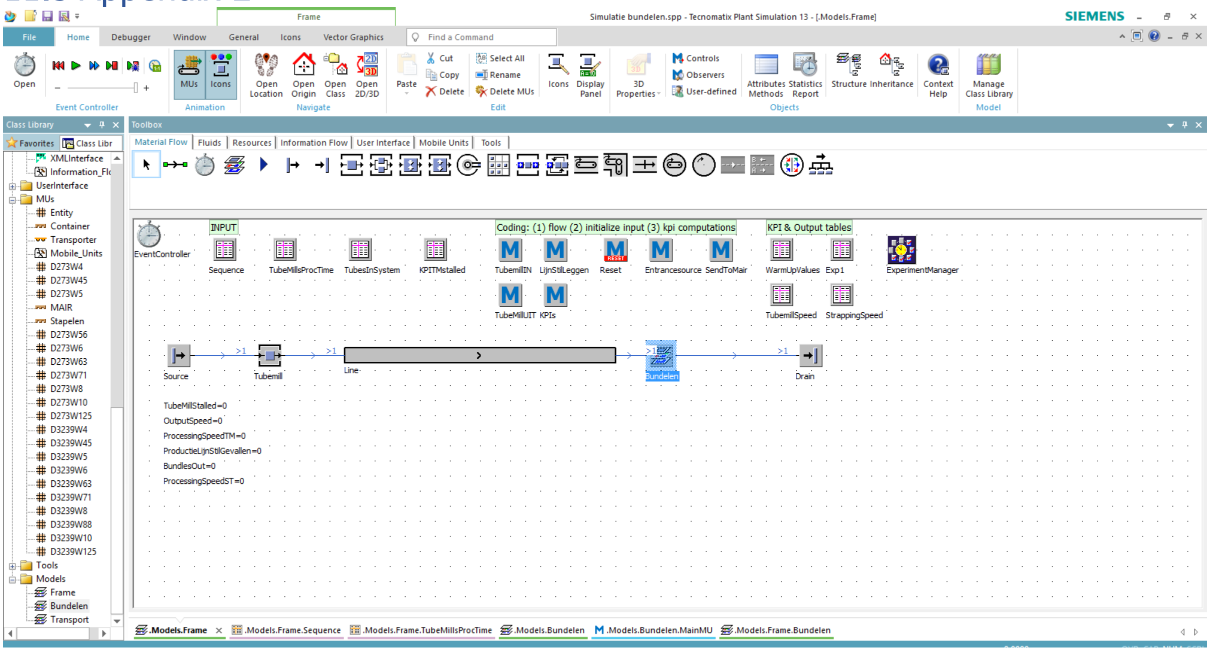

Figure 25: Rootframe

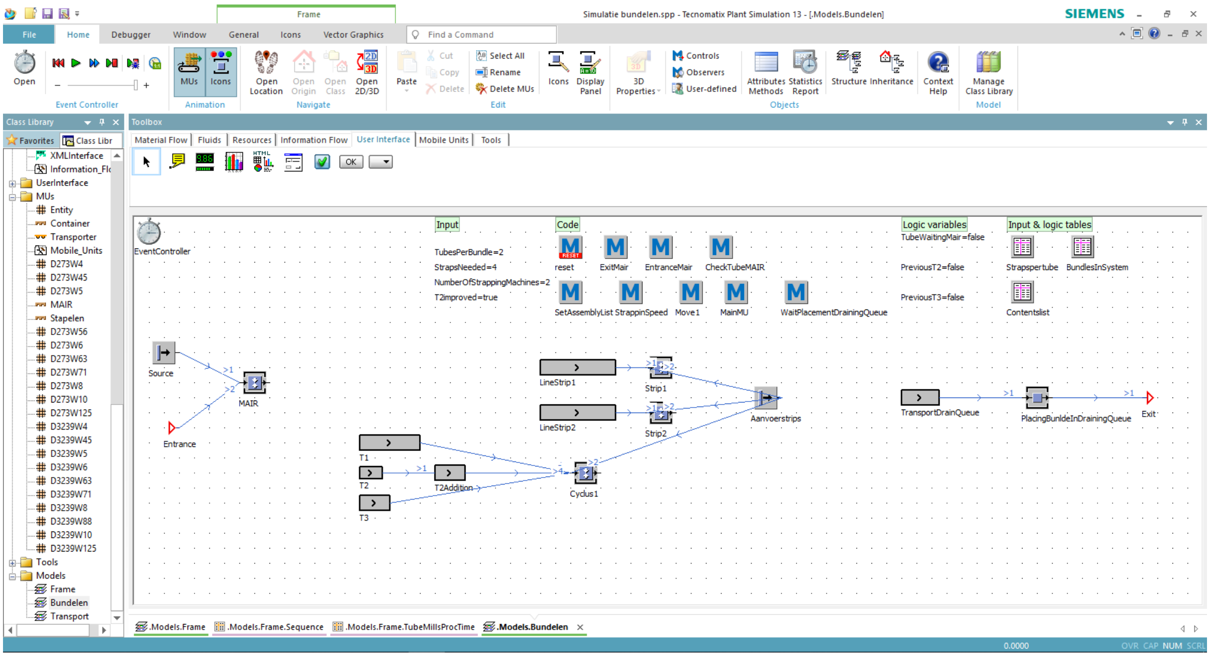

Figure 26: Bundle frame

```
param attribute: string, oldValue: any
var tijdstalled: integer

If .models.frame.line.nummu = .models.frame.line.capacity then -- if line capacity is reached, the tube mill should be stalled
    .models.frame.tubemill.failed := true
    .models.frame.ProductieLijnStilGevallen := .models.frame.ProductieLijnStilGevallen + 1
    .models.frame.KPITMStalled["TimeStalled",.models.frame.KPITMstalled.Ydim + 1] := eventController.simtime
elseif .models.frame.line.nummu = 0 then -- if the conveyor belt in fornt of the Mair is empty, the tube mill should be started again.
    .models.frame.tubemill.failed := false
    .models.frame.KPITMStalled["Timestarted", .models.frame.KPITMstalled.Ydim] := eventController.Simtime
    Tijdstalled := .models.frame.KPITMstalled["Timestarted", .models.frame.KPITMstalled.Ydim] - .models.frame.KPITmstalled["Timestalled",.models.frame.KPITMStalled.Ydim]
    .models.frame.Exp1["TimeTMStalled", .models.frame.exp1.ydim] := Tijdstalled
end
```

Figure 28: Method 'StallLine'

```
if T1.occupied or T2Addition.occupied or T3.occupied or T2.occupied  or LineStrip1.occupied or TransportDrainQueue.occupied or Cyclus1.occupied or Strip1.occupied or Linestrip2.occupied or Strip2.occupied then
    BundleInStrapping := true
else
    BundleInstrapping := false
end
```

Figure 27: Set bundleInStrapping value

```
if @.location = MAIR and BundleInStrapping = false then
    if StripsTotaal - .Models.Bundelen.BundlesInSystem["Gebundeld", @]  >= .models.frame.bundelen.NumberOfStrappingMachines then
        @.Move(T1)
    Elseif StripsTotaal - .Models.Bundelen.BundlesInSystem["Gebundeld", @] = 1 then
        @.Move(LineStrip1)
    else @.Move(TransportDrainQueue)
    end
.models.frame.bundelen.TubeWaitingMair := false
elseif @.location = MAIR and BundleInstrapping = true
If @.location = Cyclus1
    .Models.Bundelen.BundlesInSystem["Gebundeld", @ ] := .Models.Bundelen.BundlesInSystem["Gebundeld", @ ] + .models.frame.bundelen.NumberOfStrappingMachines
        if StripsTotaal - .Models.Bundelen.BundlesInSystem["Gebundeld", @] >= .models.frame.bundelen.NumberOfStrappingMachines and PreviousT2 = false then
            @.Move(T2)
            PreviousT2 := true
        elseif StripsTotaal - .Models.Bundelen.BundlesInSystem["Gebundeld", @] >= .models.frame.bundelen.NumberOfStrappingMachines and PreviousT2 = true and PreviousT3 = false then
            @.Move(T3)
            PreviousT3 := true
        Elseif StripsTotaal - .Models.Bundelen.BundlesInSystem["Gebundeld", @] = 1 then
            @.Move(LineStrip1)
        elseif StripsTotaal - .models.bundelen.bundlesInSystem["Gebundeld", @] = 2 and .models.frame.bundelen.numberofstrappingmachines > 2 then
        @.move(LineStrip2)
        else @.Move(TransportDrainQueue)
        end
end
```

Figure 30: Cyclus 1 movement logic

```
waituntil .models.frame.bundelen.PlacingBunldeInDrainingQueue.occupied = false prio 1

@.move
```

Figure 31: Hinderance bundle in draining queue

```
param attribute: string, oldValue: any
var BundleInstrapping: boolean


if .models.frame.bundelen.TransportDrainQueue.Nummu = 0 and oldValue = 1 then

    if T1.occupied or T2Addition.occupied or T3.occupied or LineStrip1.occupied or LineStrip2.occupied or TransportDrainQueue.occupied or Cyclus1.occupied or Strip1.occupied or Strip2.occupied then
            BundleInStrapping := true
        else
            BundleInstrapping := false
    end


    if .models.frame.bundelen.TubeWaitingMair = true and .models.frame.bundelen.mair.cont /= void then

    .models.frame.bundelen.mair.mu.contentslist(.models.frame.bundelen.contentslist)

        --if .models.frame.bundelen.contentslist.xdim = .models.frame.bundelen.tubesPerBundle then -- We have to make sure that the number of tubes equal tubesperbundle
   -- Output speed
      BundlesOut := BundlesOut + 1

      OutputSpeed := ((BundlesOut * (12 * .models.frame.bundelen.tubesperBundle)) / EventController.simtime) * 60
      .models.frame.exp1[2,.models.frame.exp1.ydim +1] := outputSpeed

   -- StrappinSpeed
      .models.frame.ProcessingSpeedST := ((12*.models.frame.bundelen.tubesPerBundle) / (.models.frame.StrappingSpeed["TijdOut", @] - .models.frame.strappingSpeed["TijdIn", @])) * 60
   .models.frame.Exp1[3, .models.frame.exp1.ydim] := processingspeedst
   -- average times the tubemill was stalled per hour
      .models.frame.TubeMillStalled    := .models.frame.TubeMill.statfailPortion


   .models.frame.exp1[4, .models.frame.exp1.ydim] := TubeMillStalled
```

Figure 32: Store KPIs

```
.models.frame.bundelen.TubeWaitingMair := false
if .models.frame.bundelen.tubesperBundle = 2
    .models.frame.bundelen.MAIR.ProcTime := str_to_time("25") -- 1 layer
elseif .models.frame.bundelen.tubesperBundle = 5
    .models.frame.bundelen.MAIR.ProcTime := str_to_time("50") -- 2 layers
end
```

Figure 34: Entrance MAIR

```
-- set assembly list
if ? = .models.frame.bundelen.source then
var AssyList: table[integer,integer]
AssyList.create
AssyList.writeRow(1,1, 2,.models.frame.bundelen.tubesPerBundle)
.models.frame.bundelen.mair.AssemblyList := AssyList
end
```

11.6 Appendix F

Table 7: Output experiment 'current reality'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled
D273W4	20.4	20.5	50	58.3%
D273W45	20.4	20.5	50	58.3%
D273W5	20.4	20.5	50	58.3%
D273W56	20.4	20.5	45	53.7%
D273W6	20.4	20.5	45	53.7%
D273W63	20.4	20.5	45	53.7%
D273W71	20.4	20.5	30	30.6%
D273W8	20.4	20.5	30	30.6%
D273W10	20.0	28.2	20	0.0%
D273W125	20.0	28.2	20	0.0%
D3239W4	20.4	20.5	35	40.5%
D3239W45	20.4	20.5	35	40.5%
D3239W5	20.4	20.5	35	40.5%
D3239W6	20.4	20.5	35	40.5%
D3239W63	20.4	20.5	35	40.5%
D3239W71	20.4	20.5	35	40.5%
D3239W8	20.4	20.5	30	30.6%
D3239W88	20.4	20.5	25	16.7%
D3239W10	20.0	28.2	20	0.0%
D3239W125	20.0	28.2	20	0.0%

Table 8: Output 'experiment 1'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled

D273W4	49.8	70.6	50	0.0
D273W45	49.8	70.6	50	0.0
D273W5	49.8	70.6	50	0.0
D3239W4	34.9	70.6	35	0.0
D3239W45	34.9	70.6	35	0.0
D3239W5	34.9	70.6	35	0.0

Table 9: Output 'experiment 2'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled
D273W4	23.8	23.9	50	51.5%
D273W45	23.8	23.9	50	51.5%
D273W5	23.8	23.9	50	51.5%
D273W56	23.8	23.9	45	46.1%
D273W6	23.8	23.9	45	46.1%
D273W63	23.8	23.9	45	46.1%
D273W71	23.8	23.9	30	19.2%
D273W8	23.8	23.9	30	19.2%
D273W10	20.0	36.3	20	0.0%
D273W125	20.0	36.3	20	0.0%
D3239W4	23.8	23.9	35	30.7%
D3239W45	23.8	23.9	35	30.7%
D3239W5	23.8	23.9	35	30.7%
D3239W6	23.8	23.9	35	30.7%
D3239W63	23.8	23.9	35	30.7%
D3239W71	23.8	23.9	35	30.7%
D3239W8	23.8	23.9	30	19.2%
D3239W88	23.8	23.9	25	3.0%

Table 10: Output 'experiment 3'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled
D273W4	23.8	23.9	50	51.5%
D273W45	23.8	23.9	50	51.5%
D273W5	23.8	23.9	50	51.5%
D273W56	23.8	23.9	45	46.1%
D273W6	23.8	23.9	45	46.1%
D273W63	23.8	23.9	45	46.1%
D273W71	23.8	23.9	30	19.2%
D273W8	23.8	23.9	30	19.2%
D273W10	20.0	36.3	20	0.0%
D273W125	20.0	36.3	20	0.0%
D3239W4	23.8	23.9	35	30.7%
D3239W45	23.8	23.9	35	30.7%
D3239W5	23.8	23.9	35	30.7%

D3239W6	23.8	23.9	35	30.7%
D3239W63	23.8	23.9	35	30.7%
D3239W71	23.8	23.9	35	30.7%
D3239W8	23.8	23.9	30	19.2%
D3239W88	23.8	23.9	25	3.0%
D3239W10	20.0	36.3	20	0.0%
D3239W125	20.0	35.7	20	0.0%

Table 11: Output 'experiment 4'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled
D273W4	23.8	23.9	50	51.5%
D273W45	23.8	23.9	50	51.5%
D273W5	23.8	23.9	50	51.5%
D273W56	23.8	23.9	45	46.2%
D273W6	23.8	23.9	45	46.2%
D273W63	23.8	23.9	45	46.2%
D273W71	23.8	23.9	30	19.2%
D273W8	23.8	23.9	30	19.2%
D273W10	20.0	28.2	20	0.0%
D273W125	20.0	28.2	20	0.0%
D3239W4	23.8	23.9	35	30.8%
D3239W45	23.8	23.9	35	30.8%
D3239W5	23.8	23.9	35	30.8%
D3239W6	23.8	23.9	35	30.8%
D3239W63	23.8	23.9	35	30.8%
D3239W71	23.8	23.9	35	30.8%
D3239W8	23.8	23.9	30	19.2%
D3239W88	23.8	23.9	25	3.1%
D3239W10	20.0	28.2	20	0.0%
D3239W125	20.0	28.2	20	0.0%

Table 12: Output 'experiment 5'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled
D273W4	49.8	70.6	50	0.0%
D273W45	49.8	70.6	50	0.0%
D273W5	49.8	70.6	50	0.0%
D3239W4	34.9	70.6	35	0.0%
D3239W45	34.9	70.6	35	0.0%
D3239W5	34.9	70.6	35	0.0%

Table 13: Output 'experiment 6'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled

D273W4	28.6	28.6	50	42.0%
D273W45	28.6	28.6	50	42.0%
D273W5	28.6	28.6	50	42.0%
D273W56	28.6	28.6	45	35.6%
D273W6	28.6	28.6	45	35.6%
D273W63	28.6	28.6	45	35.6%
D273W71	28.5	28.6	30	3.4%
D273W8	28.5	28.6	30	3.4%
D273W10	20.0	35.1	20	0.0%
D273W125	20.0	35.1	20	0.0%
D3239W4	28.5	28.6	35	17.2%
D3239W45	28.5	28.6	35	17.2%
D3239W5	28.5	28.6	35	17.2%
D3239W6	28.5	28.6	35	17.2%
D3239W63	28.5	28.6	35	17.2%
D3239W71	28.5	28.6	35	17.2%
D3239W8	28.5	28.6	30	3.4%
D3239W88	24.9	35.1	25	0.0%

Table 14: Output 'experiment 7'

Tube	OutputSpeed	StrappingSpeed	TubeMillSpeed	FractionTMStalled
D273W4	28.6	28.6	50	42.0%
D273W45	28.6	28.6	50	42.0%
D273W5	28.6	28.6	50	42.0%
D273W56	28.6	28.6	45	35.6%
D273W6	28.6	28.6	45	35.6%
D273W63	28.6	28.6	45	35.6%
D273W71	28.5	28.6	30	3.4%
D273W8	28.5	28.6	30	3.4%
D273W10	20.0	35.1	20	0.0%
D273W125	20.0	35.1	20	0.0%
D3239W4	28.5	28.6	35	17.2%
D3239W45	28.5	28.6	35	17.2%
D3239W5	28.5	28.6	35	17.2%
D3239W6	28.5	28.6	35	17.2%
D3239W63	28.5	28.6	35	17.2%
D3239W71	28.5	28.6	35	17.2%
D3239W8	28.5	28.6	30	3.4%
D3239W88	24.9	35.1	25	0.0%
D3239W10	20.0	35.1	20	0.0%
D3239W125	20.0	35.1	20	0.0%

11.7 Appendix G

Table 15: Input calculation

Input parameter description	Value
Processing time MAIR	50 s
Processing time strapping process without hinderance of placing the previous bundle in the draining queue	51 secs (based on the assumptions made)
Processing time: placing the previous bundle in the draining queue	40 sec
Interarrival time at the MAIR	14.4 sec
Tubes per bundle	5

The 5 tubes arrive at the MAIR in 14.4 * 5 = 72 seconds. The 72 seconds is bigger than the processing time of the MAIR, thus the MAIR must wait 12 seconds after 1 process cyclus. After 51 seconds, the bundle is strapped and placed in the draining queue. In theory, the strapping machine could process another bundle of tubes, however in practise it will have to wait for the MAIR to finish the desired bundle shape. The waiting time equals 72 – 51 = 21 seconds. After 21 seconds, the strapping process starts. The time that elapses till the end of T2 is 20,67 seconds. 21 seconds waiting time at MAIR + 20.67 seconds processing time till the end of T2 = 41,67 seconds in total. Those 41,67 seconds are greater than the processing time of placing the previous bundle in the draining queue, thus the bundle is not hindered. Conclusion: the processing time of the strapping process equals the processing time without hinderance, so 51 seconds.

11.8 Appendix H

Table 16: Cross case analysis

Tube	**TubeMillSpeed**	**Current reality**	**Experiment 1**	**Experiment 4**	**Experiment 6**	**Experiment 7**
D273W4	50.0	20.5	70.6	23.9	28.6	28.6
D273W45	50.0	20.5	70.6	23.9	28.6	28.6
D273W5	50.0	20.5	70.6	23.9	28.6	28.6
D273W56	45.0	20.5		23.9	28.6	28.6
D273W6	45.0	20.5		23.9	28.6	28.6
D273W63	45.0	20.5		23.9	28.6	28.6
D273W71	30.0	20.5		23.9	28.6	28.6
D273W8	30.0	20.5		23.9	28.6	28.6
D273W10	20.0	28.2		28.2	28.2	35.1
D273W125	20.0	28.2		28.2	28.2	35.1
D3239W4	35.0	20.5	70.6	23.9	28.6	28.6
D3239W45	35.0	20.5	70.6	23.9	28.6	28.6
D3239W5	35.0	20.5	70.6	23.9	28.6	28.6
D3239W6	35.0	20.5		23.9	28.6	28.6
D3239W63	35.0	20.5		23.9	28.6	28.6

D3239W71	35.0	20.5	[redacted]	23.9	28.6	28.6
D3239W8	30.0	20.5	[redacted]	23.9	28.6	28.6
D3239W88	25.0	20.5	[redacted]	23.9	35.1	35.1
D3239W10	20.0	28.2	[redacted]	28.2	[redacted]	35.1
D3239W125	20.0	28.2	[redacted]	28.2	[redacted]	35.1

Table 17: Legend table 15

Current reality	Strapping speed current reality
Experiment 1	Strapping speed 5 tubes per bundle
Experiment 4	Strapping speed: decreased hinder
Experiment 6	Strapping speed: decreased hinder + stronger straps
Experiment 7	Strapping speed: decreased hinder + additional strapping machine