Evaluating Impact of High-Speed Machine Line Integration at TKF

Research Information

‘Evaluating Impact of High-Speed Machine Integration at TKF’

Date: 21-10-2024
Number of pages: 45
Number of appendices: 8

Author

Thijs Hendrik Benjamin Verbeek

S2631654

t.h.b.verbeek@student.utwente.nl

BSc Industrial Engineering & Management

University of Twente

Dr.ir. J.M.J. Schutten

Dr.ir. M. Koot

Drienerlolaan 5

7522 NB Enschede

Tel. 053 489 9111

UNIVERSITY OF TWENTE.

Twentsche Kabel Fabriek (TKF)

L. Bergman

Spinnerstraat 15

7481 KJ Haaksbergen

Tel. 053 573 22 55

Preface & Acknowledgements

Dear reader,

You are starting to read my bachelor thesis with the title "*Evaluating Impact of High-Speed Machine Line Integration at TKF*". This research takes place at the Twentsche Kabel Fabriek (TKF) in Haaksbergen and is situated in the installation department. TKF's long history and expertise in cable production as well as their growth in innovative connectivity solutions provided me a valuable experience applying academic learnings in a professional environment.

Firstly, I would like to thank Lars Bergman for his guidance during this thesis at TKF and providing the right direction for the research in general. Additionally, I want to thank the TKF employees at the department for welcoming me in their work environment. Furthermore, I would like to thank Marco Schutten for being my first supervisor from the university, his feedback provided great insights on how to approach this research project and improve it along the way. Additionally, I want to thank Martijn Koot for being my second university supervisor.

Lastly, I would like to kindly thank my girlfriend, family and friends for their valuable support during the course of this research.

Best Regards,

Thijs Verbeek

Management Summary

This research takes place at TKF's installation department and focuses on the impact of the implementation of a new high-speed machine line. This machine line will replace an existing one and achieve a higher production speed. Thus, in this research we focus on how to approach the analysis of the adjusted process flow, as well as the renewed optimisation of Work in Progress (WIP) levels. This additional focus on WIP is incorporated as TKF sets their own WIP restrictions, meaning a change in the process has high influence on the WIP level and TKF's restrictions.

To approach TKF's situation we formulate the following main research question:

"What is the impact of implementing a new sheathing line at TKF's installation department cable production process on required WIP levels and the process flow?"

The research considers *"adjusted process flow"* as the main problem, with *"renewed flow analysis & recalculation WIP insufficiently executed"* being the main cause leading to that problem.

At TKF, the production process layout consists of multiple groups of machines. Every group has a function dedicated to one out of five steps in the production process of producing cables for residential or industrial construction. Reel squares are located in front of each machine line or elsewhere in the layout to serve as intermediate storage locations; this is where WIP is managed. A product can follow a wide range of combinations of process steps, depending on the type of cable it is.

The position of the new machine line is situated towards the end of the production process where it applies a layer of coating around a cable for protection. The utilisation rate of the current sheathing line is 90.34%, which is high compared to the other lines. The new machine will be able to pull a cable through the machine at twice the speed, which is 160m/min. We are able to measure performance at the installation department layout using different metrics.

We construct a theoretical framework and essentially divide our main research question into two parts; one considers the analysis of adjusted process flows where the other considers the evaluation of WIP levels. For the former, the Theory of Constraints (TOC) plays a significant role in managing constraints in a process and provides identification, exploitation and subordination to the constraint. Combined with the Drum-Buffer-Rope (DBR) theory, the process can be synchronised around the constraint, allowing for new adjustments to be made.

The perspectives of Kanban and CONWIP are primarily used to evaluate WIP levels, however they also play a role in analysing an adjusted process flow. Kanban limits WIP at each process step specifically while CONWIP takes WIP into account more globally and sets limits for the entire process. They both help to ensure a stable WIP level and to manage process performance, we use these methods to implement TKF's WIP level restrictions (24-48 hours of WIP in front of each machine line).

We construct a discrete event simulation model and make it as representative as possible in order to implement and fully understand the impact of the methods we gather in the theoretical framework. The simulation model serves as a medium for testing the methods we apply to TKF without having to make changes in the real-life situation.

To measure and quantify output, we use average waiting time (*AWT*), Output of articles with the amount of process step they perform and the average throughput time (*AVT*)

The average waiting time directly links to throughput and output, we can use these metrics to analyse the impact of our changes in the simulation model with regards to the requirements of this research.

Finally, we implement the methods in the simulation model and measure output, after which we can compare to the current situation. From this we approach the solution to the main research question. We see in the baseline configuration experiment that the average waiting time at the new sheathing line is drastically lower than most other machine lines, at 15 minutes which is an expected result. In total, we conduct five other experiments where we first utilise two TOC concepts and one DBR concept. These experiments help to approach the analysis of the adjusted process flow. The two experiments involving Kanban and CONWIP respectively indulge in the renewed optimisation of WIP levels.

The first method, TOC, provides insight on the identification of the new constraint/bottleneck after implementation of the new machine line. This constraint is insulation line 4 with an average waiting time (*AWT*) at its reel square of 3 hours and 3 minutes, we also identify insulation line 5 as a constraint with an *AWT* of 3 hours and 5 minutes.

We then exploit this constraint according to key TOC step 2, where we redistribute work from insulation line 5 to insulation line 3. This exploitation leads to a decrease in *AWT* for insulation line 5; this is 1 hour and 51 minutes. *AWT* does expectedly increase for insulation line 3 with 2 minutes, this is an acceptable consequence. Key TOC step 3 involves subordination, we subordinate the process to insulation line 4 as division of work for that line is not possible. This leads to large increases in *AWT* at other machine groups, for example stranding line 5 sees an increase from 1 hour and 51 minutes to 2 hours and 9 minutes.

DBR methodology lets us limit the reel buffers of the insulation lines to a capacity of 17-35, 12-23, 13-26 for insulation lines 3, 4 and 5 respectively. We base these capacities on TKF's WIP level restriction of 24-48 hours. *AWT* drops significantly across all insulation lines. For insulation line 3, it decreases from 1 hour and 5 minutes to 41 minutes; for insulation line 4, it falls from 3 hours to 2 hours and 29 minutes; and for insulation line 5, it reduces from 2 hours and 44 minutes to 2 hours and 22 minutes. Other machine lines also experience sharp reductions in *AWT*. However, this improvement stems from the rope component restricting the flow of articles, which results in a lower total articles produced (*TA*) compared to the baseline. However, by adjusting the rope strategy, we could maintain its benefits without sacrificing overall throughput. The buffer slightly increased utilisation rates of the bottleneck machines.

In the WIP evaluation, we reintroduce TKF's WIP level restriction through the Kanban methodology, controlling article movement based on reel square capacity. When capacity hits or exceeds 48 hours, the article waits until there's enough room. This approach, applied per machine line, pushes *AWT* up, especially for the stranding machines and sheathing 5, where *AWT* jumps from 2 hours and 16 minutes to 2 hours and 49 minutes. These machines appear frequently in production paths, making them more sensitive to changes. *AWT* for insulation line 3 rises slightly, but insulation line 4 and insulation line 5 improve, with insulation line 4 dropping from 3 hours and 3 minutes to 2 hours and 34 minutes, and insulation line 5 falling from 3 hours and 5 minutes to 2 hours and 53 minutes. Despite these gains, congestion builds at the stranding lines, driving their *AWT* higher and reducing *TA* from 435 to 430. This is due to articles performing one step often contain the stranding step, where the congestion is the largest.

Based on the conclusions we make from the methods; we offer recommendations to TKF. Utilising the Theory of Constraints consistently as a tool and regularly applying the five key steps is vital in keeping track of adjustments in their process. Bottlenecks/constraints can shift and should continuously be kept track of. Additionally, to evaluate necessary WIP levels, TKF should implement CONWIP over Kanban methodology, as this created favourable results. Kanban can still be a viable option when already put in place. Lastly, TKF should measure the actual new machine performance to gain insights on real-world outcomes. To analyse continuously will help to truly create an overview of their new situation. Changing the way of analysing helps to create a more comprehensive view as well.

Table of Contents

1. Introduction

This report describes research performed at the company Twentsche Kabel Fabriek (TKF). Section 1.1 introduces the company and describes the specific department where this research project takes place, with which it gives a description of the distinct phases of this project. After this, Section 1.2 mentions the problem context. The latter helps to provide a closer insight on where the main problem TKF is experiencing takes place. Finally, in the last sections (Sections 1.3 & 1.4) of this chapter, the way of conducting this research and the structure of the report provide insight into the general way of working, along with the deliverables of this research.

1.1 Context Introduction

This section starts with introducing the context of this research and the general research objectives, where Section 1.1.1 discusses the context of the company where this project takes place and Section 1.1.2 looks at that context more specifically by analysing the specific department within the company. Section 1.1.3 gives explanations about the term 'work in progress' (WIP) and 'bottleneck'.

1.1.1 Company Introduction

As a subsidiary of Twentsche Kabel Holding Group (TKH), starting in 1930, TKF is a company involved with providing connectivity solutions using a broad portfolio of cables, systems and services, spread over the production facilities in Haaksbergen, Lochem and Eemshaven. The location in Eemshaven achieved completion to start production of the higher voltage cables used for e.g. subsea projects; this was done in Lochem. In Lochem, the focus will be on middle voltage cables, now the Eemshaven location has become active. The biggest location of TKF, which I situated in Haaksbergen, will then move their middle voltage department and make room for special cable manufacturing, additional to the large low voltage cable industry.

Different market segments are targeted using their wide variety of company departments spread out over the various locations. Contextualizing this research at TKF leads to primarily considering the facility in Haaksbergen which is divided into 6 departments: Installation, Multi-Conductor, Energy, Fiber Optics, Wire Factory (DRAFA) and Expedition. The observed problem focuses this project on one single department and avoids an unmanageable scope, and so the installation department is where the problem for this project is situated.

1.1.2 Department Introduction

Within the installation department, high quality cables and systems for utility and residential construction industry are produced. As cable production in this department is relatively standardized, a complete portfolio of cables is offered, produced in bulk and kept in stock. These cables generally have a low voltage capacity as a defining specification and are produced on a high speed.

The production process within the installation department's process is composed of three or four main steps, depending on the type of cable produced (see Chapter 2 for a detailed overview). This department gets their 'raw material' from the department (DRAFA) manufacturing the appropriate copper cable sizes and lengths. Within this process of the installation department, there is one production step that will be altered with the introduction of a new machine line. Chapter 2 introduces further explanations about this production step and the alteration.

1.1.3 WIP & Bottleneck Definition

This section introduces a brief description of the term 'WIP' and 'bottleneck' as these terms are relevant for this research and in the continuation of Chapter 1 they are used extensively for the first time.

We us the term 'WIP (Work in Progress)' extensively, which is why we provide a definition:

WIP refers to the inventory of partially finished products that are being processed for manufacturing but are yet to be completed, this includes all inventory between the starting point of a process and the point where the inventory becomes finished products.

Hopp et al. (1998) define the functionality of WIP as; '*WIP is directly observable and can be used to indicate the amount of stock flowing through the production cell.*'

WIP also is used to relate to the state of production orders, as WIP can assign a location in the production process for an order at any time. When the level of WIP is analysed in the production process and at each process step it is measured, an evaluation can be made to see how stock defined under an amount of WIP flows through the process. For example, if the amount of stock flowing through the production process before the first step is much higher than at a last step, somewhere in the process there is an obstruction, which can be situated at any of the process steps. This means WIP can be an indication for obstruction but does not necessarily have to be one. To analyse and make decisions with regards to this obstruction, it can be measured what processing times and utilisation rates are, for example. With that, the state and flow of production orders can be related to WIP. The amount of WIP is generally analysed and measured at material buffers or in front of machine lines. Different strategies can be applied taking WIP into account, where it is kept low in most instances but that is not necessarily the case for all situations.

A bottleneck is defined by Roser et al. (2001) as the place or machine in a production process with the longest waiting time and processing time, thus the longest active period. The bottleneck is most likely to influence the throughput of the entire system that it is situated in, more than other places or machines in that system and is seen as something to mitigate.

1.2 Problem Context

This section explains the context of the problem tackled during this research where it motivates the problem in Section 1.2.1. Additionally, in Section 1.2.2 the managerial statement strengthens that motivation. In Section 1.2.3 sheds light on the main problem and gives a definition of the context. Section 1.2.4 presents an overview of the problem area using a cause-effect cluster. In Section 1.2.5, the discrepancy caused by the problem is compared by the requirements of TKF for the new situation.

1.2.1 Problem Motivation

In one part of the process within the installation department, which is one of the last steps (sheathing), TKF will replace an older machine. This replacement will create a higher performance of this part of the process. A higher production speed will be achieved. Next to that, ideally the machine will combine two production steps in the future, which will also increase production speed. As a consequence of higher production speed, the intermediate stock levels (WIP) and throughput rate will be influenced, and an impact will be made on the general flow of the production process.

1.2.2 Managerial Statement

The managerial statement by TKF.

"The replacement of one of the current sheathing lines for a new high speed sheathing line will have an impact on the flow and work-in-progress (WIP) storage locations in the installation department's production process. TKF wants to gather advice and recommendations for the effects of fitting in their new sheathing line on the workflow and WIP locations in the production cell."

Sections 1.2.3 and 1.2.4 discuss more detailed requirements.

1.2.3 Problem Definition

The main problem in this research is the '*adjusted process flow with unoptimised WIP levels*'. We define this problem as the situation where TKF experiences a different situation than what they are used to normally because of the replacement of one of their machine lines. Requirements are not met because the expected flow of the process is adjusted, Section 1.2.4 sheds light on the causes leading to this main problem. This adjustment of the expected flow also lead to different required WIP levels, which are not determined yet.

We note the fact that this replacement of the machine line is not literally seen as a 'problem' but requires action and therefore is the 'problem' treated in this project. (Heerkens & Winden, 2021)

1.2.4 Cause-Effect Cluster & Main Problem

The cause-effect cluster introduces an overview of the main problem treated in this project and the (in)direct causes and consequences, starting with the main problem definition.

A larger version of this cluster mentions the cause at the core as well as the benefits and/or consequences and the problems out of scope. The full cause-effect cluster can be found in Appendix A

As the new machine causes an '*adjusted process flow with unoptimised WIP levels*', Table 1 presents the decision between the different potential causes and their relevancy for this project. Motivation leading to the decisions to make this investment into a high-speed sheathing line are also included in the larger cluster as benefits.

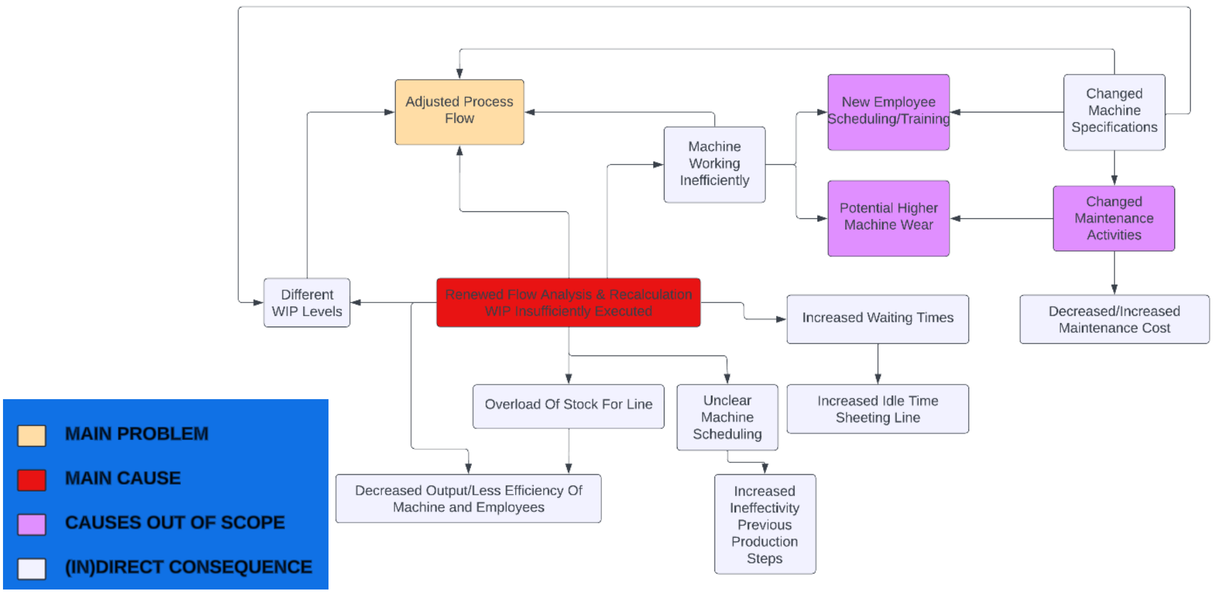


Figure 1: Problem Cluster

The main cause is '*renewed flow analysis & optimisation WIP levels insufficiently executed*'. The different links between the main cause and other aspects of the cluster space have their own implications as well, as Figure 1 shows. '*Renewed flow analysis*' and '*changed machine specifications*' could both be seen as that main cause, as they have no causal problem linking to them. However, we select the main cause to be the first one, as this has higher relevance to the research and is impactable, which the latter is not.

The final branch in Figure 1 links to causes and effects in purple, partly driven by the risk of machines working inefficiently. Employees may need new training for new schedules, and average machine wear could increase due to higher usage to meet production demands. However, these issues, as Table 1 displays, are outside the project's scope.

Cause/Effect	Improvable (yes/no)	Improvement Feasibility	Reasoning
Adjusted Process Flow	Yes	Very High	Within the scope of this project
Renewed Flow Analysis/Recalculation WIP Insufficiently Executed	Yes	Very High	Within the scope of this project
Different WIP Levels	Yes	Very High	Within the scope of this project
Increased Waiting Times	Yes	High	Within the scope of this project
Machine Working Inefficiently	Yes	High	Within the scope of this project
Changed Machine Specifications	No	Low	Not adjustable within the scope of this project, only causal effect
Unclear Machine Scheduling	Yes	Medium	Can be done, would create an overly broad scope for the limited timeframe as this is more a planning matter
Overload of Stock for Line	Yes	Very High	Within the scope of this project
Higher Machine Wear	Yes	Low	Out of scope
New Employee Scheduling/Training	Yes	Low	Out of scope, however, is indirectly improved
Increased Idle Time Sheathing Line	Yes	High	Within the scope of this project

Table 1: Cause-Effect Analysis

1.2.5 Problem-Caused Discrepancy

The main problem focuses on how implementing the new sheathing machine affects the entire production process with altering the flow and resulting in changed WIP levels. The research aims to analyse this discrepancy by comparing TKF's desired production schedules and goals with the reality caused by the new machine and identifying how to bridge the gap.

The key issue is that the current WIP levels, defined in hours of work, do not account for the higher speed of the new sheathing line. TKF's requirement is to be able to keep the production line operational for 24 hours at any given time, with WIP levels supporting at least 24 to 48 hours of work. This ensures maximum efficiency by maintaining a consistent flow of work to the machines, balancing different production speeds for various products.

Thus, the WIP levels must be adjusted to accommodate the new machine, ensuring continuous operation and keeping the process efficient. While keeping WIP levels low may seem ideal, TKF's goal is to maximize machine utilization and efficiency by having adequate WIP to keep all machines active. The problem is that current WIP levels do not reflect the new machine's performance, and the adjusted flow has not been properly analysed.

1.3 Research Questions

The main research question of this research provides guidance for coming to relevant answers and results for both this research and TKF. This question is:

"What is the impact of implementing a new sheathing line at TKF's installation department cable production process on required WIP levels and the process flow"

Research questions:

1. *What does the current situation without the new machine line look like with regards to production process layout and flow?*

To solve the main research question, an idea of the current situation for calculating and planning the WIP levels takes attention in Chapter 2, where a sketch shows how the situation should be seen and interpreted and what should be similar after the implementation or what should be different with regards to performance of the department, production flows and other performance measuring indicators.

A. *What is the production process layout?*

Looking at the entire department's structure, this sub question looks into the process surrounding the production line we consider giving an overview of the situation.

B. *What are the operational characteristics of the current sheathing line and how will these characteristics differ after implementation of the new sheathing line?*

This sub question assesses the current sheathing line under normal conditions, assuming there are no machine failures or any other disruptions. It determines what the requirements are for it to run efficiently. This involves analysing the WIP at the current machine line and its impact on the process as we assume WIP directly influences the process flow. Another aspect is the comparison of performance, planning and efficiency between the two machine lines.

C. *What performance does the installation production process generally achieve?*

This question creates more information about the current situation and how the current sheathing line performs. The findings from this question can be seen as a benchmark for the new line, taking into account the performance that is meant to be reached with this process improvement. It is considered globally as well as specifically for each production step.

D. *What are expectations and requirements from the new sheathing line?*

2. *What planning methods for analysing adjusted process flows and WIP level evaluation in production processes applicable to TKF's situation are known in literature?*

This research question consists of three sub-questions and Chapter 3 displays the process for finding the answers to the question.

A. *Which methods exist in literature for analysing adjusted process flows in production processes?*

Methods to analyse an adjusted process flow help to approach the situation of TKF. We consider methods known in literature and treat this sub question as a knowledge question.

B. *Which methods exist in literature for WIP estimation in production processes?*

The current planning methods TKF uses for WIP estimation can be used for WIP estimation again but have to be altered to the new situation. This question analyses methods that might not be used currently. A knowledge question thus appears to look into the possibilities for how to perform WIP estimation.

C. *How can the methods be implemented and used with regards to the research's objective?*

3. *What medium can be used to apply and fit the methods into the situation of this research at TKF?*

Chapter 4 provides the answer to research question 3 by providing the structure for implementing the methods.

A. *How do the methods fit in TKF's situation and what are the criteria for selecting a simulation model?*

We aim to find what the theoretical approach is to implement these methods and provide criteria for using a simulation model as a medium.

B. *How can a simulation model be structured for the methods to be applied to TKF's situation?*

We aim to find how to implement this theoretical approach to be able to test with the methods we find in Chapter 3

4. *How does the analysis of the adjusted process flow and evaluation of WIP levels perform in the situation with the new sheathing line?*

Chapter 5 discusses this research question. We analyse the solution design and implement the methods found in Chapter 3. We then consider the performance of the combination of these methods with the solution design and finally analyse the output the methods provide.

A. *How do the simulated WIP evaluation and adjusted flow analysis compare to the current situation?*

We compare the proceedings of the analysis to the current situation to see if with the new sheathing line, the criteria and requirements set by TKF, are reached.

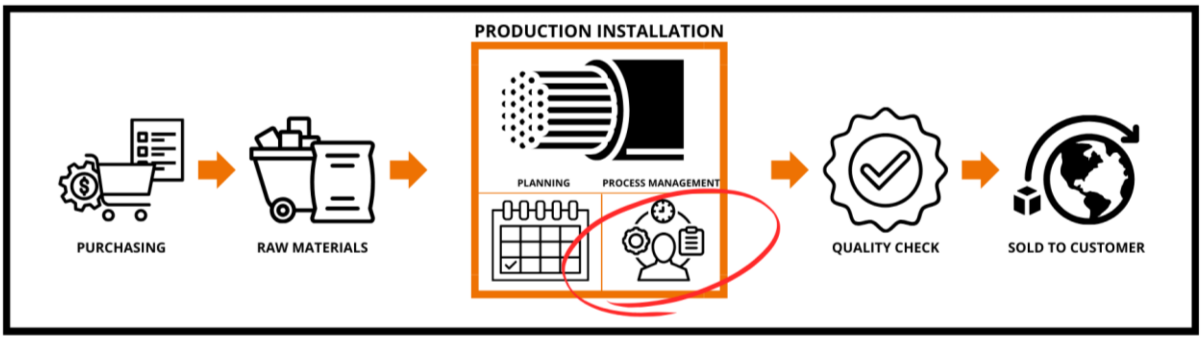
B. *What output do the methods provide?*

To analyse the adjusted process flow and evaluate WIP levels, we observe and discuss the output of the methods we implement.

1.4 Project Scope

Considering the limited timeframe for the execution of the research project, we mention a project scope. As mentioned, the project takes place in the installation department. Looking at the steps for a production order at TKF, Figure 2 presents the global process which contains all those steps.

Figure 2: Global Scope



From the different steps in creating and in the end, selling a product, this figure discusses those different steps. Important is the location of the production step, in the installation department, this is highlighted as this already narrows down the scope from the global overview of the cycle a product goes through, to the department. Looking with more attention within the production at the installation department, a product is considered in multiple steps as well, one of which is process management. During this research, this is what is looked at.

The new production line will ultimately also include combining two steps in the production process, further speeding up the production of the products and additionally, other WIP levels at the earlier production steps will need to be assumed as well. This is part of the problem that will be kept out of scope as this requires totally new recalculations and will not be implemented right away. Additionally, impacts on the step before the product enters the installation production facility are not taken into account as this is an entirely independent process where they make appropriately sized copper cables with the department's own planning strategies. Lastly, some production orders that only perform one step in the installation department are kept into account but without their previous steps at the other departments. This concept where production orders perform steps at other departments is important for this research as it occurs often.

2. Current Situation

This chapter looks at the current situation at the installation department of TKF, gives an overview of what the production process layout looks like and provides insight into the changes made. Section 2.1 introduces the department and the process, after which Section 2.2 discusses the production process more specifically. and its sub questions. Section 2.3 provides a reflection of the production cell data, such as production volume, varying performances and specific production step performances. Section 2.4 performs an analysis of the old sheathing line compared to the new sheathing line with all relevant aspects connected to that. This chapter integrates research question one:

'What does the current situation without the new machine line look like with regards to production process layout and flow?"

2.1 Department Introduction

Section 2.1.1 explains the general structure of the department and Section 2.1.2 gives a definition of each main production step.

2.1.1 General Structure

In the installation department, insulation is where the process starts, then stranding, after which the process flows to either braiding or sheathing. After sheathing, the process is either done or flows back to braiding. This 'path' of a product through the process is the most general and traditional at the department. We discuss the process steps more extensively in Section 2.1.2. However, in Chapter 4 we see that products can have different kind of paths as well. After installation the product is checked and delivered to the customers. For each production step, there is more than one different machine line. Furthermore, in the installation department there are WIP storage locations. In practice, these locations are squares before each production step where reels are collected and put in a waiting line in front of a machine.

2.1.2 Process Steps

The sheathing line is discussed more intensively in Section 2.4, however below we present a concise definition of each main production step, where each number represents the part of the cable that is added in the step and highlighted in Figure 3:

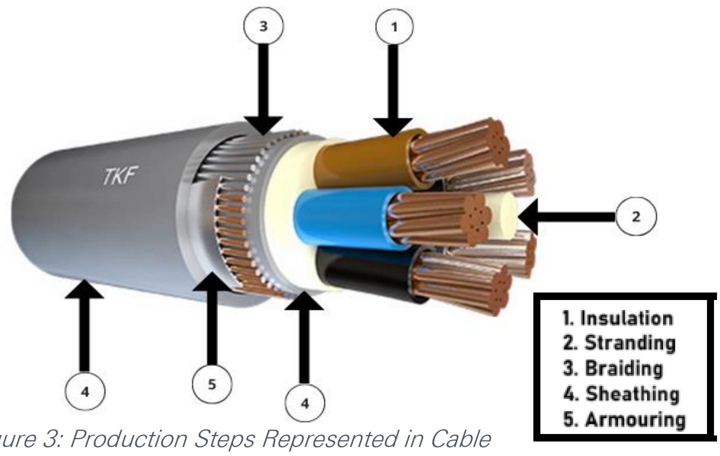


Figure 3: Production Steps Represented in Cable

1. Insulation: *The incoming copper wires that have been made to length and thickness for each production order are isolated by use of a coating for protection of the cable and to make it conductive.*

2. Stranding: *As most cables are composed of different isolated wires, a stranding step is needed where the cables are gathered together and able to flow into the next step as a compact product.*
3. Braiding: *When the stranding process is completed, the braiding step help to make sure the isolated wires are stuck together and made more compact. The most important addition of this step is the application of steel or coper wire braided around the cable for protection.*
4. Sheathing: *Depending on if this step is performed before or after braiding, an inner or outer sheath is applied to protect the cable from the tough structure of the metal braiding. The outer sheath finishes the product. These sheaths are a plastic coating.*

A cable standardly produced in this department has a thickness of 2.5mm2. Ideally, this department is active during 24 hours with the ability to produce a cable length of 80 meters per minute at the sheathing line in question, the machine line is called M6. Considering other less standardly produced products, an additional step that can occur during the production is armouring.

5. *Armouring: In this step, a braided or folded metal construction is applied to protect the cable from external forces.*

2.2 Production Process

The floor plan in Section 2.2.1 gives insight into the positioning of the machines and general structure of the production cell. In addition to that, product paths shown in Section 2.2.2 provide a general understanding of how a production order moves through the system.

2.2.1 Floor Plan & Product Paths

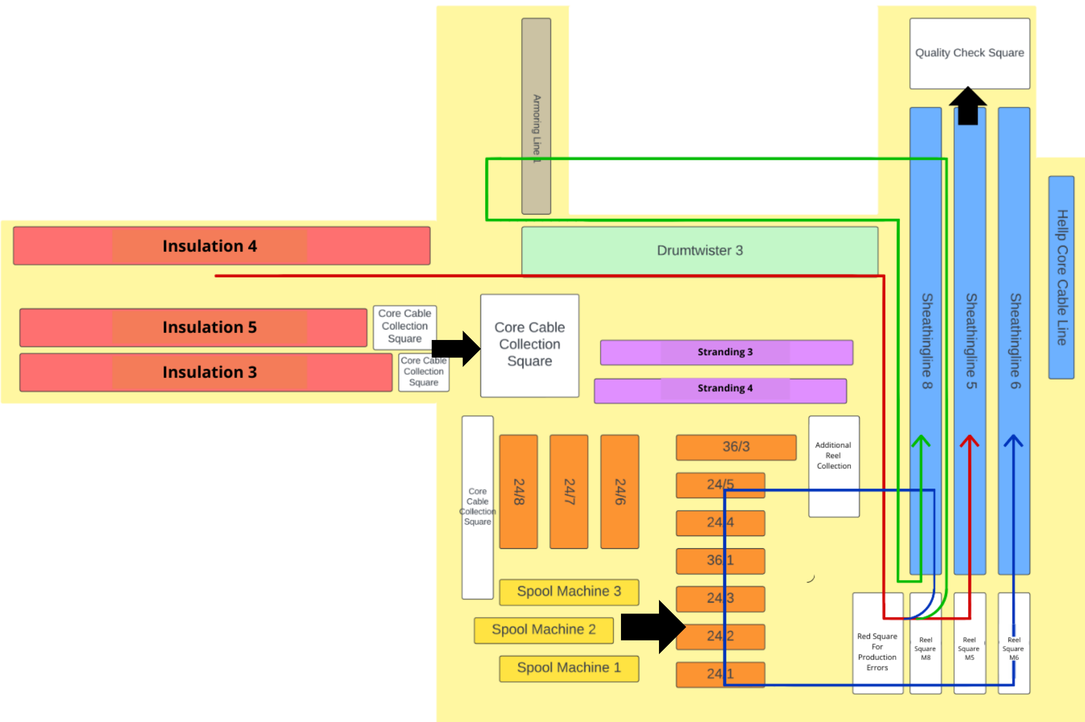


Figure 4: Floor Plan with Most Common Product Paths

The floor plan in Figure 4 (full page version of floor plan with and without paths in Appendix C) presents an overview to show how machines are positioned within the area of the installation department as well as the most common production paths.

The assorted colours help identify difference in machine lines in Figure 4. We assign a value like 24/1 in the reference name. With this 24/1 braiding machine there are 24 small cable reel carriers, and this is number 1 of that type, so 24/1. The other values can be interpreted likewise. For the other machine lines, Section 2.1 gives a description of the work performed there. The drumtwister machine serves as a stranding machine as well but on a different scale where larger cables can be produced. The machines named as 'stranding' in Figure 4 are eligible to process cables with a diameter of up to 6mm and up to 8 core cables at a time. The drum twister performs a comparable process with cables larger than 6mm and more than 8 cables at a time. Cables flowing through each production step are transported on reels (Appendix D).

The uncoloured squares serve as a place for reel collection (Figure 5). These squares are used as a production order collection place, either in front of a machine line, or as a storage space for later. Below the sheathing lines, there is a square called '*red square for production errors.* This square is used for reels carrying wrongly produced cables, and which need to be reviewed for further action before carrying on in the process.

To visualise the process flow and opportunities for a cable to flow through the system, Appendix C presents the most common production paths, where they all have the same production steps at first. Each article follows the red path until after the first sheathing step, where a blue and green path can be identified in addition next to the red one.

Path 1: Red = Isolation – Stranding – Outer Sheath

Path 2: Red Flowing into Green = Isolation – Stranding – Inner Sheath – Braiding – Outer Sheath

Path 3: Red Flowing into Blue = Isolation – Stranding – Inner Sheath – Armouring – Outer Sheath

When investigating TKF's problem, these paths are taken into account, additional paths are used in Chapter 4, as a lot of different paths do exist.

Figure 5: Reel Collection Square: Installation Cables for Residential Construction

Figure 6 gives a more schematic business process flow. This highlights the parts where there is a connection between physical production lines, and TKF's IT systems. These systems are taking into account production orders where production times, waiting times and other specifications about the products are kept track of. We use this in creating necessary data for judging the production process flow, like waiting times for the entire production process and numbers of orders in front of a machine. This data is collected in the Enterprise Resource System called Navision.

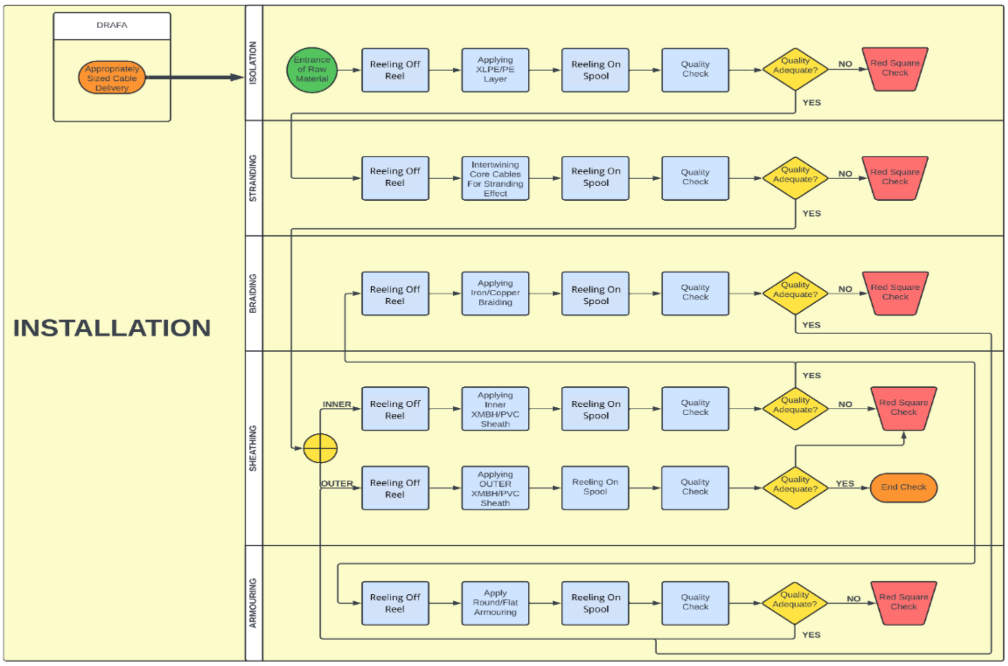


Figure 6: Schematic Process Flow Installation Department (Full Page Version in Appendix)

2.2.2 Significance Reel Squares

The reel squares each serve a different purpose (Figure 5). There are squares with high significance in analysing the process flow, like the squares next to the stranding machine lines. These squares are classified from A-J and using this classification, orders for a combination of core cables can be placed at one of these squares to combine the different semifinished products to go into the stranding machine lines. A specific core cable is only produced when the article in a production order consists of that specific core cable. The process the production order goes through can only continue when the core cables are collected at the square it is assigned to before the stranding step. This strategy differs from a more traditional strategy; that difference is found in that the core cables are only produced when needed and they are generally not produced in bulk.

Lastly, the reel squares in front of machine lines like at the sheathing line, denote capacity for WIP as well and determine the production flow. Table 2 provides insight into the capacity of these squares.

Location	Capacity
Stranding (A-J)	5 Core Cable Reels
Insulation	8 Raw Material Reels
Sheathing	16 Cable Reels
Braiding	1 Cable Reel Per Machine
Armouring	1 Cable Reel

Table 2: Reel Square Capacity

2.3 Installation Production Cell Data

Several types of performance measures provide an overview of the scale of production in the installation department which gives an insight into what is the department's output within cable production. The flow in the departments of TKF is closely monitored which helps to evaluate the performance of the different departments; Section 2.3.1 takes a look at this for the installation department. Thereafter, Section 2.3.2 makes a note on the varying performance the department might have. Section 2.3.3 mentions the performance of each step in the production cell.

2.3.1 Production Volume

The production volumes are measured in different ways per year, per month or on daily basis. Examples are the average produced cable weight per day (Figure 7) and average weight of cable produced per man hour (Figure 8).

Figure 7 visualises the average cable weight produced per day and gives insight to TKF's installation department's performance normally. This example as well as the example in Figure 8 allows us to make comparisons after analysing TKF's adjusted process flow.

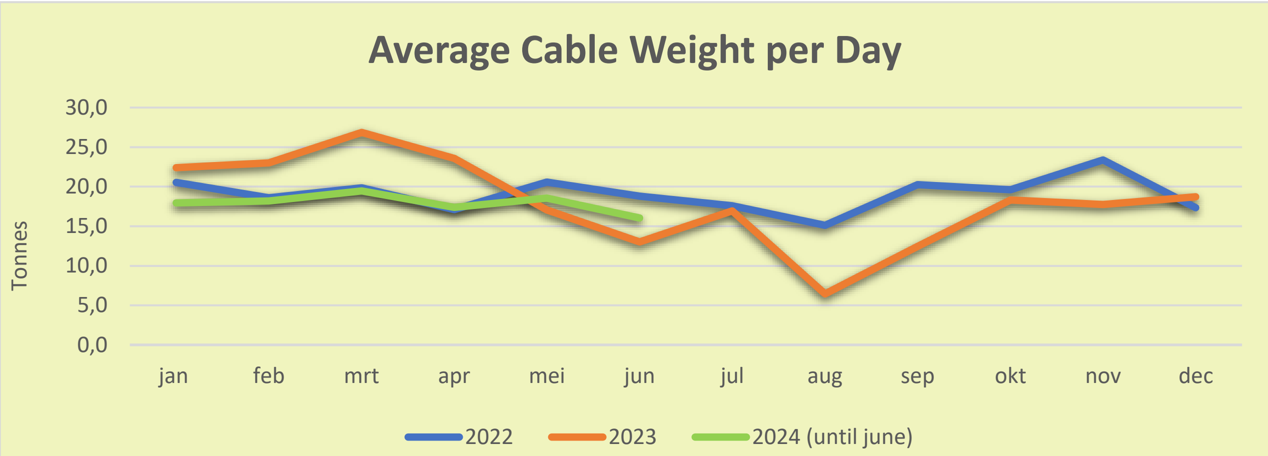


Figure 7: Average Cable Weight Per Day

The performance metric of the installation department, which is more tailored to the context of the problem, is average produced cable weight per man hour. We take man hours into account when analysing the adjusted process flow and looking at performance of the machine lines.

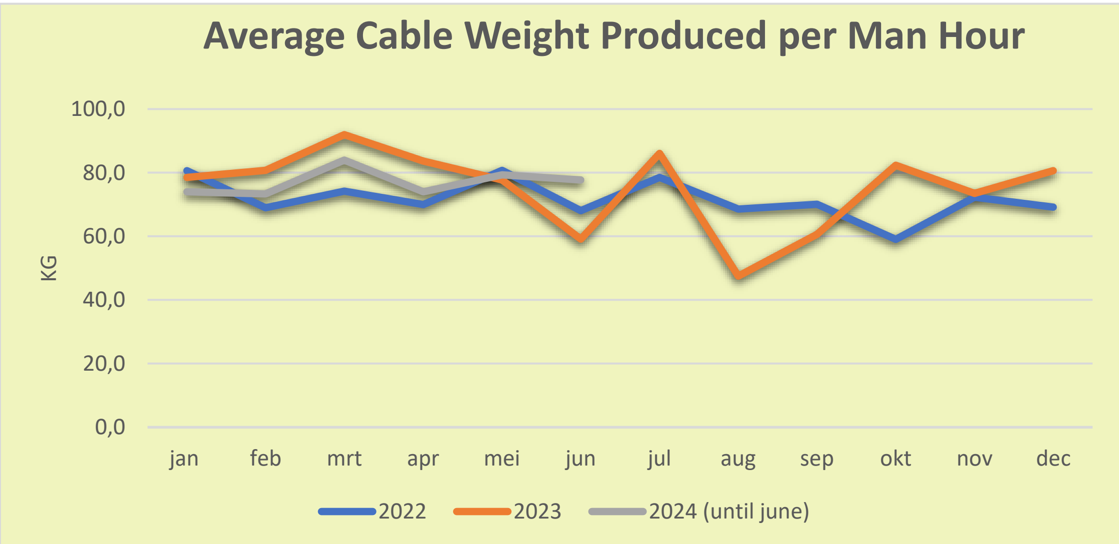


Figure 8: Average Cable Weight Per Man Hour

Comparing both graphs, we identify the same patterns with for example the spike in performance in July 2023. However, taking the scale on the y-axis into account, an observation is made that the performance per man hour is less varying than the metric used in the graph above. This indicates, solely looking at these two graphs, that man hours make a difference in performance. This is something that is only marginally influenced by this project the problem definitions describe. Therefore, keeping performance metrics like this in mind is important for measuring performance later in the new situation. As we observe, production volumes vary around 70 kg to 80 kg per man hour with the current system setup.

The cable reels each contain various amounts of lengths of cable, meaning the production time per article can significantly differ.

2.3.2 Varying Performance

When we consider the department's performance, a variety of situations can exist, which can each influence this performance. The product flows through the production cell in routes that are mentioned earlier in Section 2.2. We see these routes as the most occurring ones. However, additional routings exist and with fluctuations in product type demand, the production schedule changes a lot.

Another influence that can be both unpredictable and predictable is the machine downtime. TKF calculates maintenance times and takes them into account while constructing the production schedule. However, there can also be unexpected disruptions caused by machines breaking down or parts wearing off more quickly than anticipated, as each machine line consists of a lot of various parts. This does not directly impact the performance of one production order at one machine, but obviously in the whole production cell, it can cause major disruptions.

2.3.3 Process Steps Performance

When we look more specifically at the steps within the process, performance is measured as well and displayed. This forms input in Chapter 4 as well, for solution generation and simulation modelling. It is important to define and give value to these performance metrics per step. The process steps performance is deducted from the dataset of the installation department over the years 2022 and 2023.

As mentioned, the steps consist of multiple machine lines each. During the evaluation of the data for the performance metrics of these steps and machines, we analyse which steps contains machines that have high similarity between their performance metrics compared to each other, and which steps do not have that. Depending on the degree of similarity between the performance metrics, a decision is made to define the metrics per machine, or we define them for all the machines in the step simultaneously. For example, the insulation step consists of quite a variety in the values of the metrics, so all the lines (INS) are split up. On the contrary, the braiding machine lines can be classified with average times for each line. The processing and setup times for the machines are taken as an average which includes a calculation over the average cable length and processing time. These processing times in combination with the average waiting time are linked to throughput time.

Table 3: Average Processing/Setup Time Per Machine

Process Step	AVG Processing Time (min)	AVG Setup Time (min)
Insulation Total	73,1	31,0
• INS 3	55,2	26,3
• INS 4	78,2	43,4

• INS 5	86,0	23,3
Stranding Total	N/A	N/A
• STR 3	150,2	26,3
• STR 5	123,7	35,9
• DT 3	107,0	98,8
Sheathing Total	77,3	17,3
• SHT 5	77,0	15,8
• SHT 6	65,7	23,5
• SHT 8	89,2	12,7
Braiding Total	748,3	36,7
Armouring 1	332,2	90,1

We give utilisation rates and use them as input for the simulation model. We calculate these as follows:

$$(Scheduled\ Man\ Hours\ /\ Available\ \ Hours) \times\ 100\%$$

Scheduled man hours are the number of hours an operator is assigned to a machine and thus the time the machine can be active. For stranding machines, an operator can assist at two machines at the same time, which is why the active man hours on this machine are compensated accordingly. The same goes for braiding machines, where multiple operators can be present.

Available Machine Hours are a constant, calculated as follows:

$$8\ Hour\ Shift\ \times\ 21\ Shifts\ \times\ 48\ Work\ Weeks\ =\ 8064\ Available\ Hours$$

This considers the setup used by TKF, where they compensate for holidays and lower availability of manpower by setting 48 work weeks in a 52-week year. Per week there are 7 days consisting of 3 eight hours shifts, which explains the first part. In an ideal situation, the machines would work all of the 8064 available hours, so each shift would be covered. As we denote in Section 2.3.1, this is important for getting an accurate representation of performance.

Considering this formulation, Table 4 presents utilisation rates per machine line.

Table 4: Utilisation Per Machine Line

Machine Line	Utilisation (%)	Utilisation (Hours)
Insulation 3	60,21%	4855
Insulation 4	77,06%	6214
Insulation 5	78,39%	6321
Stranding 3	58,54%	4721
Stranding 5	79,85%	6439
Drumtwister 3	44,56%	3593
Sheathing 5	92,77%	7481
Sheathing 6	90,34%	7285
Sheathing 8	76,46%	6166
Braiding (Average)	61,15%	4931
Armouring 1	26,26%	2118

As can be seen, the sheathing lines have a high utilisation rate, where other production step's machine lines lag behind in that. This is a first motivation for why the sheathing step is a bottleneck in the current situation.

2.4 Old & New Sheathing Line

The sheathing line is the main priority in this research when the production process is considered. This section discusses what is changed with regards to the old M6 sheathing line compared to the new M10 sheathing line in Section 2.4.1, with an explanation on how to measure these differences in Section 2.4.2 and expectations for the performance in Section 2.4.3

Further explanation about the machine line help to understand this part of the production process and to see how the machine functions a full overview as well as the input materials for this machine are given in Appendix E

2.4.1 Comparison Sheathing Lines

M10 (New Sheathing Line) has two main differences compared to M6 (Old Sheathing Line), M10 will be placed in the same spot as M6 in the process layout of Figure 4 in Section 2.2.1.

The two main differences can both be found in step 4 of the sheathing process (Appendix E), the extrusion step. The extruder is larger in M10 than M6 meaning a cable can be pulled through at a faster speed. The goal is that M10 will process the cables of a thinner size. Additionally, co-extrusion will be possible leading to a decrease in material usage.

Next to the extruder, the cooling trough also leads to the ability to speed up the sheathing process. This cooling trough will be longer meaning the cable does not have to spend the same time in the trough as with the smaller version, and therefore it can be pulled through faster. These two aspects increase the machine speed, the leading KPI for the sheathing machine.

2.4.2 Key Performance Indicators (KPIs)

The performance of this line can be measured in diverse ways depending on settings chosen by decision makers. These settings are defined in a MIK (Machine Instel Kaart) so a Machine Instruction Card. The settings depend on the kind of cable is next to be produced, and what the specifications of that cable are with tensile strengths, materials and other configurations.

As Section 2.3.3 presents, there are different KPIs to take into account. In this section we define them for the sheathing line. Starting the process of sheathing, the machine is set up according to the MIKs, the time this takes is the first KPI mentioned which is setup time. Processing time is the next KPI, where the time an order is processed in the line is measured. Additionally, the sojourn time is these two together, where the setup time is measured from the first point of handling a production order in the machine. The last machine-specific KPI to mention is machine speed, which can differentiate for each different production order, and the speed the machine is setup for is specified in the MIK. Lastly, in Section 2.3.3 utilisation of this machine is also mentioned, which is important to take into account as well.

Processing time is directly linked to the machine speed, which is 80m/min for M6, this is the main sheathing-specific KPI to look at while analysing the impact it has on the adjusted process flow.

2.4.3 Performance Expectations

The goal is to double the sheathing machine speed to 160 m/min, improving performance and reducing material usage compared to the previous setup. This increase, moving from the M6 to the M10 setup, is expected to halve processing time, allowing for higher output within the same timeframe. Operators are expecting updated production requirements as the focus shifts to TKF's thinner cable portfolio, affecting product distribution on each sheathing line when the machine is implemented. Consequently, production planners will need to adjust article assignments and monitor work-in-progress (WIP) levels (24-48 hours) to prevent bottlenecks. Stakeholders expect these changes to shift bottlenecks within the production process and are concerned with overall flow impact.

2.5 Conclusion

To conclude, Chapter 2 answers research question 1:

"*What does the current situation without the new machine line look like with regards to production process layout and flow?"*

Sub questions (A-C) of research question 1 help to answer it, where firstly we determine that the production process layout consists of multiple groups of machines. Every group has a function dedicated to one out of five steps in the production process. Reel squares are located close to the machine lines to provide input, and are used as intermediate storage locations, they also determine the amount of storage space until there is overcapacity. A product can follow a wide variety of paths through the layout, depending on the type of cable it is.

The installation department uses different metrics like cable weight produced per man hour to keep track of performance.

The current sheathing line has a utilisation of 90,34%, which is high compared to other machine lines. The current sheathing line will be swapped for a newer version, which has the ability to pull a cable through the machine at a faster speed and will also be able to produce cables of a thinner size. This new machine line will be expected to produce twice as fast at 160m/min, eliminating the observed bottleneck and it will decrease the usage of materials. The performance of the machine is measured by taking setup time and processing time, while also combining the two into sojourn time.

To find methods to approach the problem formulated in Chapter 1 and the process description of this Chapter, we perform a literature review in Chapter 3.

3. Theoretical Framework

This chapter discusses literature focused on methods to deal with an adjusted process flow and methods to identify the constraining factors in a process, next to that the chapter approaches WIP level evaluation methods. This chapter thus answers research question 2:

'What planning methods for analysing adjusted process flows and WIP level evaluation in production processes applicable to TKF's situation are known in literature?'

Section 3.1 start with a description of how we select theories to apply to this research and approach the solution to research question 2.

Section 3.2 then describes the Theory of Constraints, which in combination with the Drum-Buffer-Rope theory in Section 3.3 helps to analyse adjusted process flows. The Theory of Constraints helps to analyse the potential new bottlenecks the adjustment of the flow of a process creates by identifying and managing those bottlenecks. The Drum-Buffer-Rope theory then builds on that by providing a structured approach on how the bottlenecks dictate the process flow and how synchronisation to those bottlenecks can be managed.

Section 3.4 offers a lean manufacturing perspective, where we specify our focus on managing WIP restrictions through the Kanban and CONWIP approaches. While the theories in Sections 3.2 and 3.3 also consider the WIP topic, the emphasis of the theories in Section 3.4 is focused on how the two methodologies can help to control and limit WIP levels.

Section 3.5 connects the methods in Section 3.2 and 3.3 to analysing adjusted process flows and Section 3.6 discusses the connection of WIP level evaluation with the methods.

3.1 Theory Selection

We part research question 2 in two parts; analysing adjusted process flows and WIP level evaluation. We look for theories applicable to each of the parts through a systematic literature review.

Starting with analysing adjusted process flows, we found that TOC is applied to approach mostly the theoretical side of a research problem, which in combination with DBR allows the researcher to follow a framework to identify the problem and solve it later. The choice for TOC also links to the first step of it. Identifying the constraint is what we already perform in Chapter 1 and 2, which is why TOC offers a clear pathway to build further with the that.

WIP level evaluation methods are more abstract in nature. There are different mathematical and theoretical approaches. We chose to dive into the theoretical side, this left us with few options to implement. Kanban and CONWIP are two approaches we found to be for a wide variety of research objectives in literature.

3.2 Theory of Constraints (TOC)

The Goal (Goldratt, 1984) introduces the 'theory of constraints'; this is a management methodology that takes steps to identify and improve the most limiting bottleneck within a production process or other organisational system. This theory provides a wide overview for improvement of processes and focuses less on individual component within a process.

TOC uses the logic that every process has a limiting factor, which can be one or more and determines its overall output. According to Goldratt (1984), improving isolated constraints with no identification of their connection to the entire process has a small effect on the overall output. This is why the theories argues that optimising the 'main' constraint more likely results in an increase in throughput and productivity of the process.

There are 5 key steps in applying TOC (Goldratt, 1984):

1. *Identify the Constraint:* The application of TOC starts with identifying the first constraint that restricts the process to achieve maximum output and efficiency. This constraint can be any aspect within a process, which at TKF could be the capacity of a reel square, machine line or other objects. This constraint or bottleneck dictates the flow and performance of the whole process.

2. *Exploit the Constraint:* In the second step, the constraint is used to the maximum without providing any new resources. This allows TOC to use current resources to the largest extent instead of instantly adding new resources to solve the constraint. This step involves optimisation, reconfiguration or adjustment of intermediate stock.

3. *Subordinate Everything Else Except the Constraint:* All other components in the process should support the constraining component. To avoid blockage in the process, all the other components are aligned with the production rate of the constraint to prevent overproduction. This is preferred in TOC to not waste resources on process steps that do not improve output or efficiency.

4. *Elevate the Constraint:* After exploitation and subordination, the constraint is improved when the previous two step did not increase the performance of the process enough to annul the constraint. In this step, new resources are added to increase the capacity of the constraint.

5. *Repeat the Process:* TOC includes a vision of continuous improvement, where after the improvement of one constraint, the view is shifted to another constraint that could appear after. This is repeated with every change, or every time output and efficiency do not comply with the norms.

While TOC provides the larger overview of improving a process, several theories can be used to improve the performance of constraints in step 4. However, narrowing down to the details of TOC, Goldratt (1984) states it is vital to perform a determination of what the cause of the constraint is and make clear what actually needs to be analysed and improved, before starting any solution generation. This gives high importance to step 1 in TOC.

An aspect to avoid using TOC is focusing too much on the identified constraint, as it can cause overlooking a larger systematic problem in a process. The right balance between focusing on the constraint while keeping the overview TOC provides, is also vital.

3.3 Drum-Buffer-Rope (DBR)

The drum-buffer-rope theory is used in improving output and efficiency of a process by optimising a constraint. It is seen as TOC's solution to improving operations, it involves configuring and monitoring of the process/system (Mayo-Alvarez et al., 2024). Where TOC focuses on identifying and managing with the primary constraint, DBR is a tool to schedule the workflow based on the constraint.

DBR controls the release of jobs or resources in the system in accordance with the constraint (Thurer et al., 2017). Figure 9 shows a DBR system for a single bottleneck station.

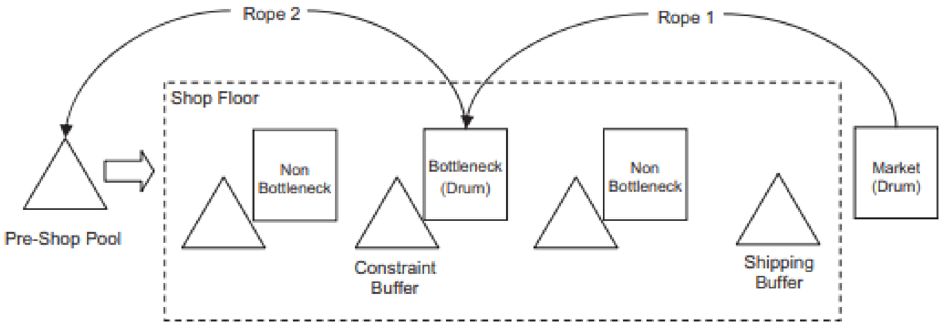


Figure 9: Drum-Buffer-Rope System (Thurer et al., 2017)

In this system, the drum is the constraint which has and forms the basis for the process around it to follow. The buffer is placed both in front of the constraint and after to control process variation. The buffer can be time or WIP defined in time, as with TKF. The drum should always have WIP in front of it to make sure it performs at its maximum efficiency, again a principle used at TKF. The buffer behind the drum should be able to store all of the output of the drum, so that when the drum functions less efficient, the processes behind it are more stable and can have a normal supply of WIP. The last component is the ropes, one of which is the communication channel from the drum to the beginning of the system (Thurer et al., 2017). When the drum lowers in performance, the rope signals the order release to input WIP at a lower rate and align it with the output rate of the drum. Thurer et al. (2017) states that a maximum limit on the number of jobs is released to the bottleneck but not yet completed is established and a job is released when the number of jobs is below the limit. The other rope subordinates the system to the constraint/drum and signals forwards from the drum.

3.4 Kanban & CONWIP

While TOC in combination with DBR focuses on constraints and the bottleneck of a process, another perspective is lean manufacturing. This perspective is focused on improving efficiency of the process.

The global concept of lean manufacturing maximises resource utilisation through minimisation of waste (Sundar et al., 2014). Lean manufacturing features subtopics to enable the execution of the theories it proposes. One of which is Kanban; this can be used to restrict WIP at each specific step in the process, when WIP is restricted to an upper or lower bound (Pettersen et al., 2008). Kanban is traditionally classified as a reorder point system but with a more visible reorder point and widely considered as both a pull and just-in-time (JIT) system. A pull system incorporates the policy to produce according to demands, rather than predicting them and creating a capacity that is always enough. Bonney et al. (1999) state that a pull system is in close relation with just-in-time, and one does not perform without the other, which Kanban takes into account.

Another subtopic of lean manufacturing similar to Kanban is CONWIP, which also uses a pull perspective in essence but can be classified as a hybrid between push and pull (Spearman et al., 1990). The difference between Kanban and CONWIP is that CONWIP considers the WIP level on a more global level, where KANBAN considers it process step specific.

A study analysing the performance of a Kanban approach to WIP restriction and comparing it with the CONWIP approach (Pettersen et al., 2008) includes a simulation model to visualise the process they perform the study with. They state their experiments show the importance to keep track of WIP and to use it as a tool to moderate a process. The findings on Kanban shows that when they restrict every inventory or queue in the process and increase the maximum amount of WIP, it was not clear at which process step they should increase the WIP. However, they noticed that placing a higher WIP level in the middle of the process increases the throughput rate. The measurement of mean lead time indicates that to place WIP later in the system decreases lead time. In general, Pettersen et al. (2008) made a few clear observations with regards to the Kanban approach:

- Increasing total maximum WIP increases the throughput and decreases time between jobs out.
- WIP should be divided as equally as possible, any surplus should be placed in front of the bottleneck or at the end of the system.
- Process performance has a higher variation when the total maximum WIP is increased.

The findings they made for the CONWIP approach, are as follows (Pettersen et al., 2008):

- Throughput and minimum time between jobs out are highest using a total maximum WIP for the whole process.
- A lower maximum WIP level is needed than with the Kanban approach.
- The restriction on the maximum WIP level is more closely aligned with the actual WIP levels achieved in practice, compared to Kanban. Generally, the CONWIP approach results in a lower and more realistic restriction.
- Process performance has a higher variation when the total maximum WIP is increased.
- Machine utilisation is higher using CONWIP approach compared to Kanban approach and is leaner, thus it shows a reduction of the use of resources and time.

In general, the study shows applying the Kanban approach in the way they did is ‘easier’ in a practical setting for researching and measuring the performance of a system without making any actual implementations. For CONWIP, it is hard to choose the maximum WIP level because it involves more generalisation; steps in the process are subordinated faster to a restricting step. Difficult decisions have to be made with regards to specifying the maximum WIP level based on the complete department of a production facility, or basing the maximum item-wise, where every route of the items is taken into account. However, using the Kanban approach or using the CONWIP approach when actually implementing it in real life, shows a contrast to the application in the study. In real life applications, it is found CONWIP systems are easier to implement.

3.5 Analysing Adjusted Process Flow (TOC & DBR)

In the event of part of a process changing and leading to an adjusted process flow, TOC and DBR can guide a way of analysing the adjustment. The two theories offer a perspective on how the change interacts with existing system and they can identify whether known bottlenecks and constraints have shifted and how they should be interpreted. To optimise performance after an adjustment, TOC ensures that the process is balanced again around the new bottleneck or around the existing one. Through the 5 TOC steps, identifying the constraints plays a crucial role when analysing an adjusted process flow, through this it can be identified if constraints shifted. The second step of TOC also enables the change to be exploited to the furthest extent, if it is identified as the constraint or becomes the constraint when TOC is repeated. That is the case because, as we mentioned before in Section 3.1, TOC is a continuous process which helps to keep improving the constraint after adjustment of the flow.

DBR synchronises a process and in the scenario of an adjusted process flow, it can do so by adjusting the drum with the new or existing constraint. The buffer(s) would be recalculated to the renewed pacing and the rope makes sure that the process steps before and after the drum are in line with its pacing. In general, DBR makes sure the findings in the analysis of the adjusted process flow by the TOC are used to make the adjusted process flow smoother.

3.6 WIP Level Evaluation (Kanban & CONWIP)

The two lean manufacturing concepts that Section 3.3 discusses are focused on WIP levels, where an evaluation is done of how the WIP is managed in a process. Kanban and CONWIP both use a WIP restriction, where CONWIP uses a more global approach while Kanban specifies the WIP level on a smaller scale. In an adjusted process with the need of renewed administration of WIP levels, these concepts can play a pivotal in administrating WIP levels subject to restrictions and requirements the process owner could imply. Depending on the situation, the decision is made to use the Kanban approach or the CONWIP approach. The Kanban method is more suitable for processes with more variety in production steps, where CONWIP provides a great way to treat all process steps simultaneously and optimise performance factors like throughput, lead time and costs on a global level. Both methods provide an aspect of constant evaluation. When dealing with change, we use this to support the WIP level evaluation as well as the adjusted process flow of Section 3.5, as the impacts the change in the process makes, could possibly not all be known.

3.7 Conclusion

This chapter explored the key methods available in literature for analysing adjusted process flows and evaluating WIP levels in production processes, addressing the sub questions of research question 2 and the research question itself:

'What planning methods for analysing adjusted process flows and WIP level evaluation in production processes applicable to TKF's situation are known in literature?'

First, we address sub question A:

'*Which methods exist in literature for analysing process flows in production processes?'*

TOC and DBR focus on the identification of bottlenecks/constraints in a process. TOC plays a large role in identifying and exploiting a constraint and also incorporates improvement of the constraint. DBR synchronises the process around the constraint, providing incentive for recalculation and installing elements in a process like a buffer and rope to continuously manage the process. We use this to start analysing an adjusted process flow and provide clarity on where constraints are positioned in the new situation, and how they can be interpreted.

Next, we take sub question B into account:

'Which methods exist in literature for WIP estimation in production processes?'

The perspectives of Kanban and CONWIP are primarily used to evaluate WIP levels, however they also play a role in analysing an adjusted process flow. Kanban limits WIP at each process step specifically while CONWIP takes WIP into account more globally and sets limits for the entire process. They both help to ensure a stable WIP level and to manage process performance.

To answer sub question C of research question 2:

"How can the methods be implemented and used with regards to the research's objective?"

These are methods to cover the analysis of an adjusted process flow and WIP level evaluation. When implemented, they form a holistic approach for both a new interpretation of the adjusted process flow and way to implement restrictions for the assignment of WIP levels.

4. Simulation Study Construction

This chapter presents the simulation construction, where we construct a way to structure, implement and test the methods we present in Chapter 3 through a simulation study. We approach the solution to research question 3B:

"What medium can be used to apply and fit the methods into the situation of this research at TKF?"

The structure we select is a Discrete Event Simulation Model; this approach is also used in the study on the comparison of Kanban and CONWIP we discuss in Chapter 3 (Pettersen et al., 2008) and we see it allows us to apply and experiment with all methods for TKF's situation without having to affect the real life situation. This point is important to be able to quantify our results and go beyond the theoretical approach, with a simulation model we allow ourselves to measure output the methods provide and we provide advice and recommendations based on that.

Section 4.1 outlines the conceptual model, offering a global understanding of the simulation structure. Section 4.2 introduces logic flowcharts that explain the underlying logic behind the model's code and visualises the simulation's structure. Section 4.3 verifies and validates the model. Section 4.4 discusses the warm-up period and the determination of replication of the simulation model to run properly and present accurate figures.

4.1 Conceptual Model

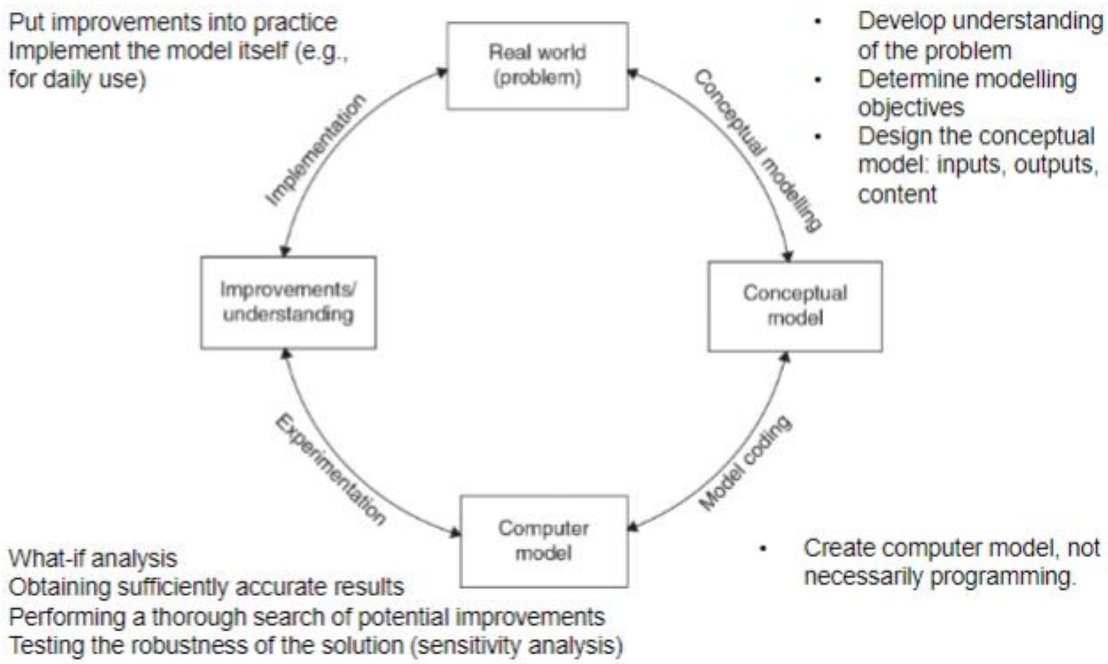


Figure 10: Simulation Study General Setup (Robinson, 2014)

The structure proposed by Robinson (2014) in Figure 10 serves as the basis for the simulation model, where we already performed the problem understanding part of the conceptual model in Chapter 1. Furthermore, the conceptual model consists of all basic layers of the simulation starting with the objectives of it in Section 4.1.1 and continues with the necessary input and what output needs to be generated in Section 4.1.2 and 4.1.3 respectively. The input data preparation is also monitored to provide details on how this is approached to prepare appropriate data for the simulation model. After this, level of detail and flowcharts forming a general structure of material flows is offered. The level of detail helps to get insight into what is included in the model and what not, this is closely related to the project scope in Chapter 1. The simulation model type is Discrete Event Simulation.

4.1.1 Objectives

To define the objectives of the simulation model, we address problem identification, goals, restrictions, and additional factors (Robinson, 2014). The primary objective is to accurately represent TKF's installation department, as we present in Chapter 2. Once achieved, this model allows for testing changes, such as reducing processing time on the new sheathing line, without disrupting real operations. With this reduction we can test our methods for the new situation with that sheathing line. The objective is thus to create the new situation without having to wait until the new sheathing line is put in the factory. Additional adjustments are explored to analyse the modified flow, requiring a realistic and reliable model.

Chapter 1 covers problem identification. Regarding restrictions, the model faces complexity due to the variety of variables and article paths within the department (Section 4.1.2). Thus, it is limited by the feasibility of accurately replicating real conditions in a simulation. To enhance validity (Section 4.4), the model must closely match TKF's requirements, further restricting its design.

4.1.2 Input Simulation Model

Navision (ERP System), Exsion (Data Extraction from Navision into Excel), and Excel provides the necessary input data, following discussions with TKF decision makers. The data covers 2022 and 2023 to include the current situation, accounting for earlier process changes. We mention the data types below. The goal of this data extraction is to generate processing times, production paths and other characteristics of the installation department's process in the simulation model.

After preparation of the data using pivot table properties along with VBA coding, the necessary data is retrieved. This data preparation and explanation of the VBA code is highlighted in Appendix F. Through this data we generate input to provide scheduling of production orders to flow through the simulation model as well as additional data we extracted to construct the simulation model, we these types of data up into different categories:

- Incoming Production Order Arrival Intensity

Per day, the incoming production order arrival intensity is different. On a Monday, naturally more production orders are entered in the system compared to the weekend as in the weekend it is less suitable to place an order. To counter an empty production process in the weekend, on Friday and Thursday the intensity is also traditionally higher compared to the rest of the week. Table 5 presents this.

Table 5: Interarrival Times for Production Orders at Each Day (Exponential Distribution)

Monday	Tuesday & Wednesday	Thursday	Friday	Weekend
1:02:20	1:10:12	43:50	41:20	200:00:00

- Core Cables Machine Scheduling

Every main article (previously referred to as a production order) is a cable within TKF's portfolio, consisting of 1 to 5 core cables. These core cables, produced during the insulation step (Chapter 2), are treated as subparts in the simulation model, as they are combined after the first step to form the main article. Therefore, data for core cables and main articles are separated into two groups. Based on cable thickness (Table 6), core cables are scheduled on insulation machine lines when needed for production, before being stranded together.

Machines	Insulation 3	Insulation 4	Insulation 5
Core Cable Thickness	1.5mm – 6mm	10mm - 240mm	1.5mm – 10mm

Table 6: Insulation Machine Core Cable Thickness Capacity

- Main Articles (Article Number Identification)

We consider main articles as products that will be an end product after the last step, differentiating from core cables which are component and thus not a main article. The main articles consist of core cables and enter the simulation in the earliest case at the second step which is stranding. After filtering the data leaving out maintenance registrations, faulty production notifications and other poor-quality data, 756 unique article numbers are registered for the main products. Some articles have possibility for entering the production process at a different step which is specified further below.

- Article Frequencies (AF)

To generate a representative schedule for the simulation model and how the production process gets orders as input, the frequency of the occurrence of each article in the data timeframe is used as the arrival intensity. Within the two years of data taken, the AF are Poisson distributed with arrival intensity λ. The AF are calculated as follows:

$$AF = Article\ Occurence/Total\ Production\ Orders$$

- Article Paths

For each process step, multiple machine lines are available (Chapter 2). Data analysis shows there are too many potential paths to generalise an article's route to one specific route in the simulation. While Chapter 2 provides an accurate overview of the production flow, it lacks the detail needed for simulation. Therefore, all article paths are recorded and used as input for the model.

- Path Frequencies (PF)

After selecting an order to be used as input for the simulation model at a given time, the path it will take needs to be determined. To make a decision for this, the same approach is taken as with the selection for the articles. PF are calculated using the same approach as the article frequencies:

$$PF = Path\ Occurence/Total\ Article\ Occurence$$

- Articles One Destination

Different articles have multiple target departments, they perform some steps in other departments and only one in the installation department, these articles are taken apart from the other main products as they do not always complete production in the installation department.

- Processing/Setup Time

After identifying the product types and their paths in the installation department, an analysis determines the appropriate input values for processing-specific attributes like machine speed, average processing/setup times, and utilisation. In the first scenario of the simulation model, the processing time for sheathing line M6/M10 is halved as an experimental factor to represent the new scenario.

Table 7 presents the key inputs we mention above to generate a production schedule in the simulation model, the table further defines the input's characteristics using identification and ranges as metrics (Robinson, 2014). Appendix F discusses filters we use to improve the quality of this input data.

Identification	Total Unique Occurrences in Data	Average Number of Paths
Core Cable	27	1
Articles	756	4,8
Article One Destination	137	1
Total (Sub) Products	920	2,3
Core Cable Paths	3	
Article Paths	3636	

Table 7: Different Input to Generate Production Schedule

Table 8 presents two other metrics to characterize input factors which are combinations and the sensitivity analysis (Robinson, 2014).

Identification	Combinations	Sensitivity Analysis
Order Arrival Intensity	• Intertwined with article frequencies for creating a production schedule	Exponential Distribution for each day with arrival intensity λ
Core Cables	• Intertwined with articles after stranding step and with core cables before stranding step	t-Test Distribution for Small Sample Normal Distribution
Articles	• Intertwined with core cables after stranding step	Many unique categories, thus multinomial distribution
Article Frequencies	• Combined with path frequencies to determine production schedule	Poisson Distributed with arrival intensity λ for each article
Path Frequencies	• Combined with article frequencies to determine production schedule	Normal Distribution for each path with mean μ
Article One Destination	• Combined with article frequencies to determine production schedule	Normal Distribution for each destination with mean μ
Processing/Setup Time (experimental factor for M6/M10)	• Combined with Article Paths and Frequencies	Exponential Distribution for each machine line with mean μ.

Table 8: Combinations & Sensitivity Analysis Input

4.1.3 Output

Output of the model is measured in KPIs necessary for this research or set by decisionmakers at TKF. In Chapter 5, outcomes for these KPI's are analysed.

KPI's:

- Average Waiting Time: *amount of time a core cable or main article spends at each reel storage buffer before entering in the productions step in the simulation model.*

Waiting time as an indicator helps to achieve an insight into where an article or core cable spends the most time inactively. This is seen as a metric to minimize.

- Throughput Time: *Total time for core cable or article to perform all production steps from the first step to being a finished product.*

Measuring throughput time and comparing it to the throughput time in the current situations helps to analyse if the process has been sped up, and if the new bottleneck does not equal the previous bottleneck in how severely it slows down the process.

- Total Articles Produced Related to Steps Performed:

The number of articles produced plotted against the production the steps the articles performed helps to gain insight into what the production volume looks like and where impacts are made.

- Utilisation per Machine Line

We use utilisation per machine line to describe how efficient they are put to use, and which machines are idle more on average.

4.1.4 Level of Detail

The model's level of detail varies across factors. For instance, production times are recorded for each specific article to maintain realism, especially given varying processing times. Similarly, the model captures the diverse production paths available for different articles, with data specifically recorded to reflect this variety.

However, certain aspects are intentionally simplified. As outlined in Chapter 1, employee scheduling and training for the new sheathing line are excluded, as they fall outside the model's scope. Likewise, sales objectives, which may shift after the machine's implementation, are not included due to their unpredictability. Additional decisions regarding model scope are detailed below.

4.1.5 Assumptions & Simplifications

The following assumptions and simplifications are added to the simulation model.

Assumptions:

- We assume that raw materials such as XLPE, PE, core filling, and MBZH are always available, as shortages rarely occur at TKF. For instance, insulation materials are consistently in stock, and the braiding machines receive a steady supply of winded iron or copper coils.
- We assume operator shortages do not occur in the model. Although operator shortages during holiday periods can reduce machine utilisation, they seldom disrupt production significantly.
- In the model, we assume disruptions and maintenance do not occur at machine lines. While disruptions and maintenance happen sporadically in the installation

department, they do not impact operations enough for us to incorporate the Overall Equipment Effectiveness (OEE) factor.

Simplifications:

- We define production paths (as discussed in Section 4.1.2) for each article number, which simplifies scheduling by separating single-step and multi-step articles. We treat core cables as separate units that flow through the system until they are combined into main articles, allowing us to schedule core cables globally.
- Reel squares serve as waiting points in front of each machine, enabling us to track delays and waiting times. For stranding machines, these squares help manage the transition from core cables to main articles once the cables are produced.
- We account for reprocessing due to faults in the average processing times, so we do not model extra steps for rework.
- We apply a global average processing time per article for braiding machines, as this step typically takes significantly longer than others.
- Since armouring is less frequently part of the process, we exclude the production of the armouring wire, used at the armouring process step. The armouring step itself is however included in the model, as the data we use to generate the production process includes articles that take on the armouring step.
- To prevent the model from encountering blockages, we introduce extra buffers that ensure smooth flow, even though these buffers do not reflect the real-life situation. Blockages are not present in the real-life, due to manual planning.

4.2 Simulation Construction

We propose several flowcharts to organize the logic used in the simulation model in Section 4.2.2, 4.2.3, 4.2.4 and 4.2.5, connecting it to the interface and the installation department as presented in Section 4.2.1. The flowcharts use terminology derived from the simulation model; these terms are made bold in the flowcharts. These terms or objects are highlighted in Appendix G as it defines the functionality of each object in the simulation model interface.

4.2.1 Construction Simulation Interface & Installation Department Layout

To construct the simulation model, we used Tecnomatix by Plant Siemens (TPS), Appendix E.1 provides motivation for the choice and presents a few terms used in the application. Appendices E.2 and E.3 present the interface and layout of the of the installation department in the simulation model, the logic flowcharts in Sections 4.2.2, 4.2.3, 4.2.4 and 4.2.5 constantly refer to the objects in the interface as well as the objects in the installation department layout.

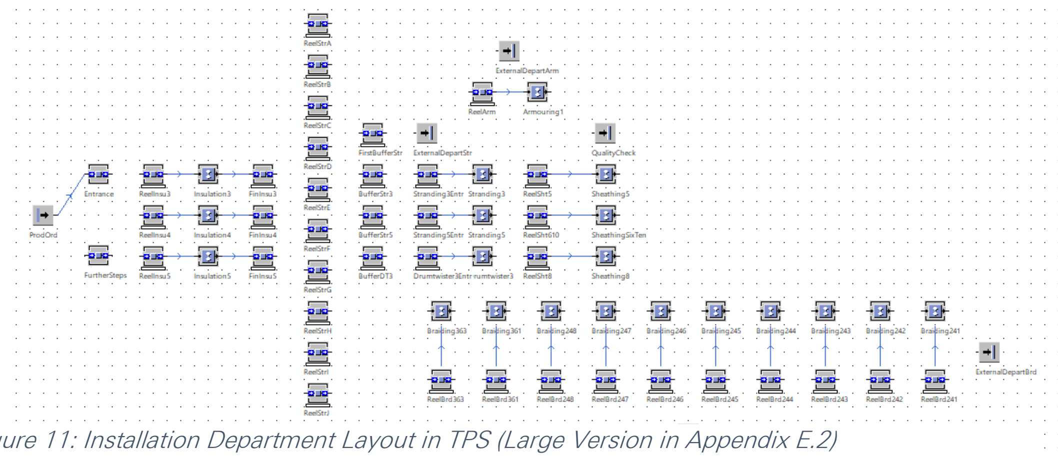


Figure 11: Installation Department Layout in TPS (Large Version in Appendix E.2)

4.2.2 Logic Flowchart Arrival Rates & Article Specification

The first flowchart (Figure 12) discusses the logic behind the initialisation of the simulation model and the first inflow of articles through the installation department. The chart thus specifies arrival intensities, the first article characteristics and their movements through the department. A legend identifies the different operands in this flowchart and in the other flowcharts in Sections 4.2.3, 4.2.4 and 4.2.5.

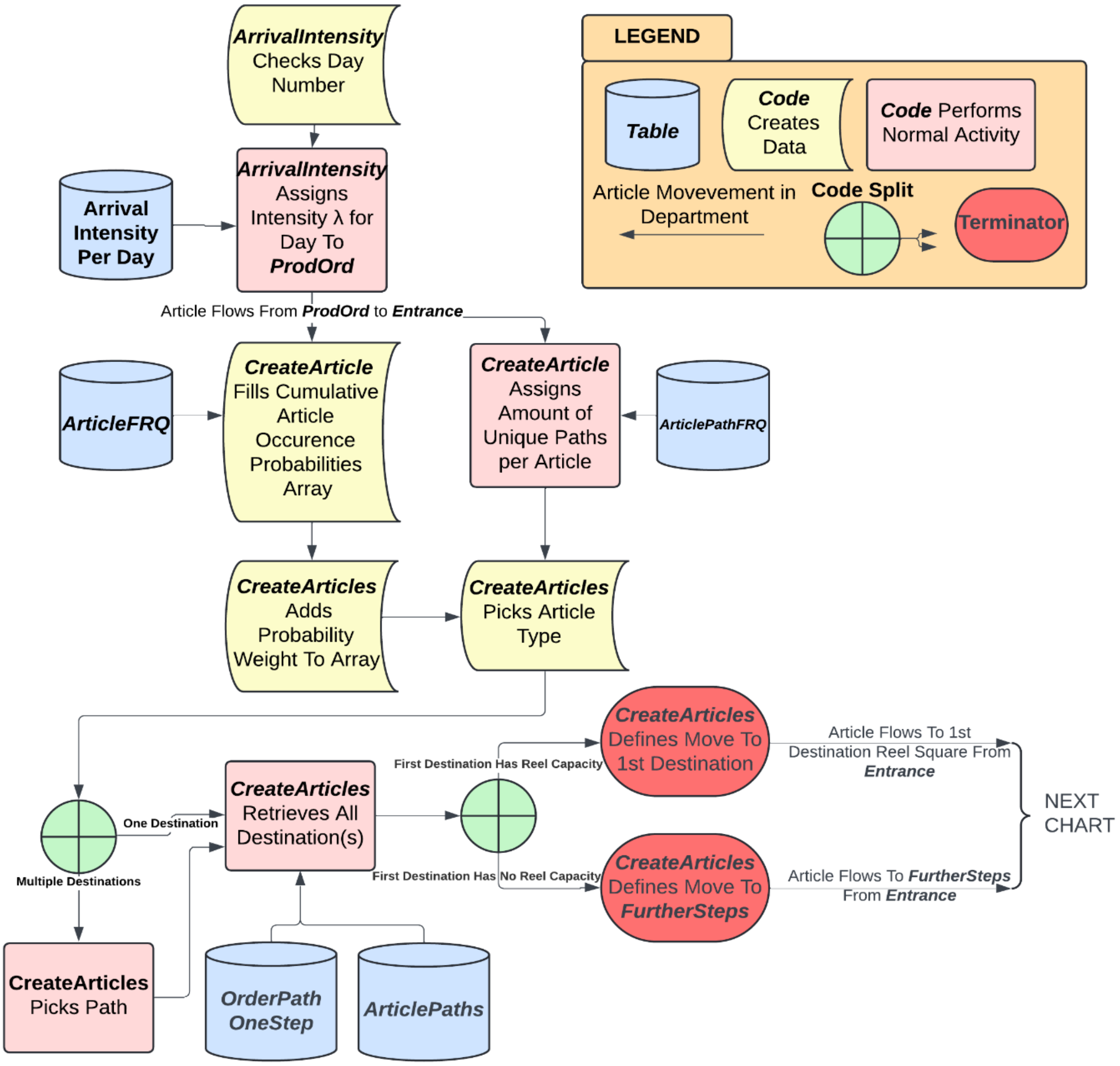


Figure 12: Arrival Rates & Article Specification Flowchart

4.2.3 Core Cable Production & Article Behaviour in Front of Stranding Step

The flowchart in Figure 13 (full page version in Appendix G.4) shows how core cable production orders are assigned to insulation machine lines, based on main articles waiting at stranding lines. If stranding lines lack capacity, core cables are still produced for articles that will go to the stranding lines when they have capacity again.

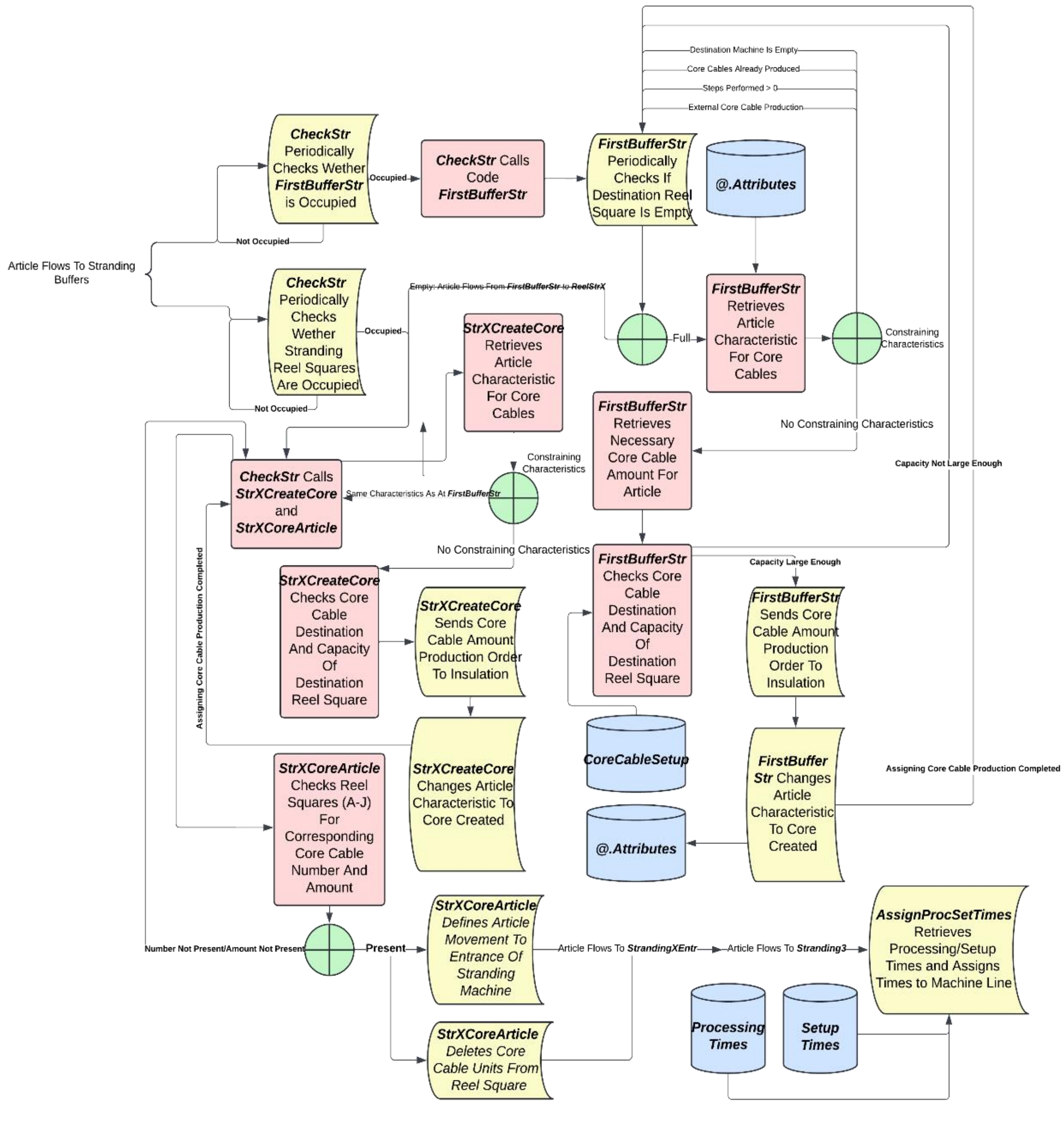


Figure 13: Assigning Core Cables & Stranding Step (StrX = Str3, Str5 or DT3)

4.2.4 Article Behaviour at Machine Lines

When an article arrives at a reel square of a machine line, it has different behaviour depending on the production step it is located at. The flowchart in Figure 14 describes this behaviour for the different types of steps.

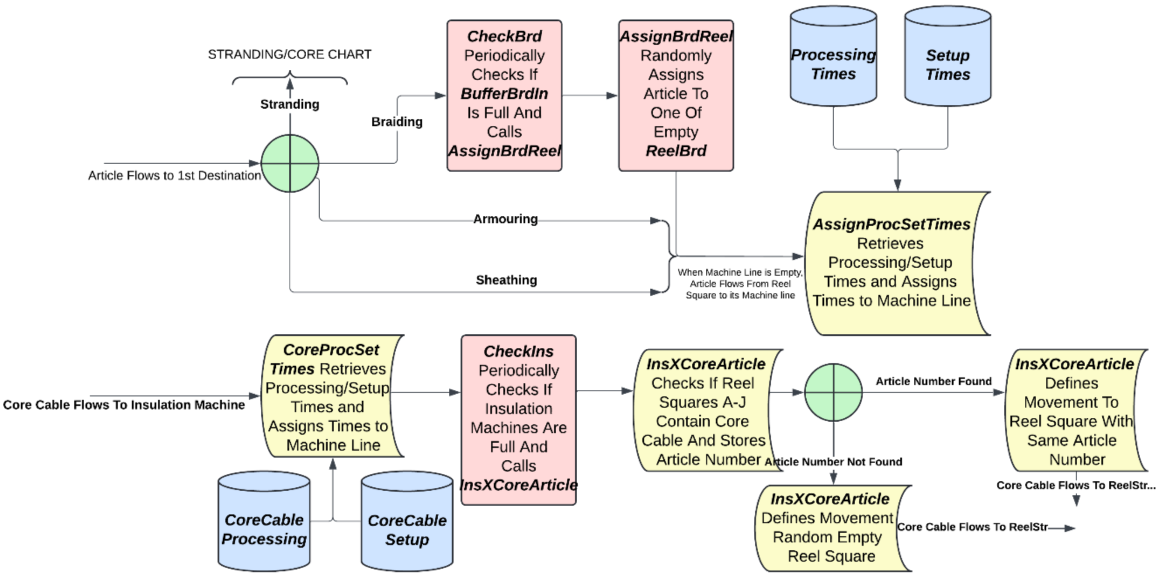


Figure 14: Article Behaviour at Machine Lines (InsX = Ins3, Ins4 or Ins5)

4.2.5 Article Behaviour After Machine Lines

When an article completes production at a machine line it can have different behaviours depending on its characteristics and location. Figure 15 sheds light on this using a logic flowchart, articles at *FurtherSteps* follow the same scheme, except for the first instance of the code creating data where it increases the steps the article performed.

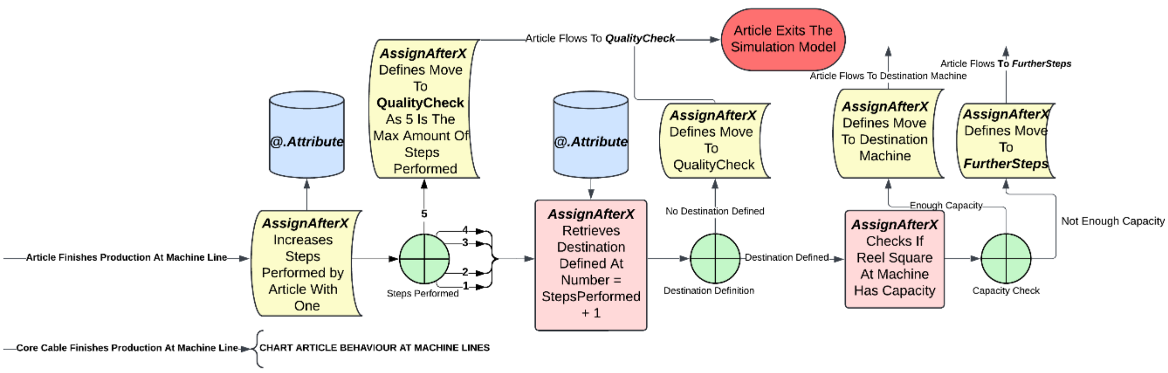


Figure 15: Article Behaviour After Machine Lines (X = Str, Sht, Brd or Arm)

4.3 Model Validation and Verification

The simulation model is verified and validated in Sections 4.3.1 and 4.3.2. Section 4.3.3 refers to the determination of the warm-up period and the replications.

4.3.1 Resemblance with Conceptual Model (Verification)

In this research, verification is an ongoing process throughout the development of the simulation model. After writing each part of the code, it is debugged by stepping through to check for errors, infinite loops, or inefficiencies. An example of this is the use of extra buffers, to prevent the system from blocking easily. Any issues are fixed, and the code is refined for conciseness to improve efficiency. Multiple reviews ensure the code is optimized, and the simulation output is assessed for plausibility, allowing easy identification of discrepancies. Additionally, the aspects from Section 4.1 are analysed to confirm everything is incorporated.

The conceptual and simulation models are developed simultaneously, ensuring automatic verification.

4.3.2 Resemblance with Reality (Validation)

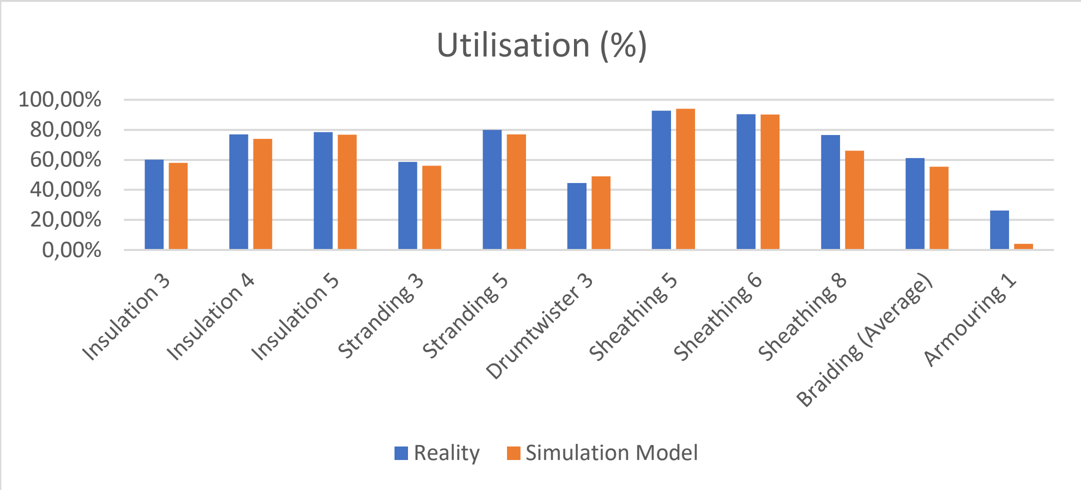


Figure 16: Comparison Chart Utilisation

To validate the resemblance of the simulation with reality, utilisation of the machine lines in the simulation model and in the real situation are compared. This is the clearest metric retrieved from the original dataset of the real-life situation and the comparison is shown in Figure 16. This shows all machine lines have a comparable utilisation, except armouring. The explanation for this is the dataset used to create the article paths, armouring was taken out of the installation department at TKF at some point in the two years used for the dataset, so it occurs less than assumed from the reality utilisation rate. Additionally, the armouring machine line has less significance as it is taken out of the installation department completely in 2024. On average, the simulation model's utilisation rates differ with 2.92%, without armouring.

4.3.3 Warm-Up Period & Replications

We run the simulation model for an amount of time that will get rid of the initialisation bias, which is the case when a realistic general condition has been reached (Robinson, 2014). Minimising the width of the confidence interval about the mean of simulation output determines the correctness of the warm-up period. We do this with the marginal standard error rule (Assadi, 2024). With a few replications we take the mean value of one key metric of the simulation model. By assessing their graph, we determine what the warm-up period is. The key metric is utilisation, measured for the three stranding lines.

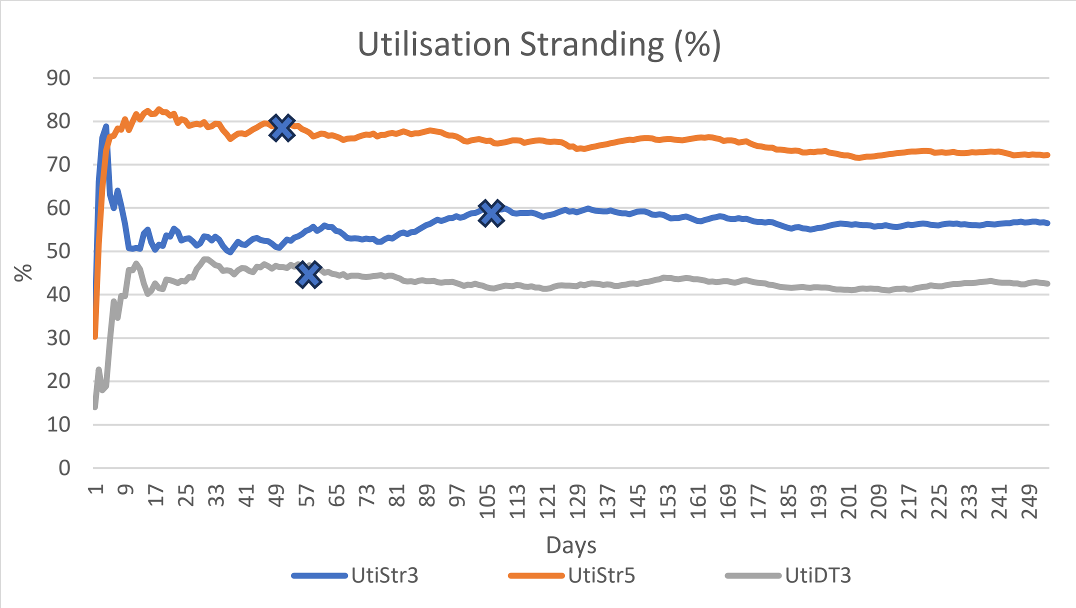


Figure 39: Utilisation Stranding Lines

Figure 39 shows the utilisation of the three stranding lines in the model, here we can determine with the visualisation in the graph what the warm-up period is. The longest needed period for the variable is leading, in this case that indicates that the stranding machine with the longest period before its graph shows well-conditioned behaviour. We see after 105 days, all three machines show normal behaviour in their output, so this is the time period we used for the warm-up.

We determine the number of necessary replications using another key metric, being ***average total throughput time.*** We use these replications to get a representative average of our key performance indicators. The graphical method allows us to determine the number of replications. A graph with the mean of the key metric values plotted against the number of replications used gives an overview of when the number of replications is sufficient, this is the case when the graph becomes flat, meaning the confidence interval around the mean is sufficiently small and the key performance indicators can thus be taken as accurate. Figure 39 shows the graph to determine replications. We observe at approximately 20 replications, the graph starts to flatten out, which is why we select this number as the right amount.

4.4 Conclusion

This chapter primarily discussed sub research question 3:

"What medium can be used to apply and fit the methods into the situation of this research at TKF?"

By constructing a simulation model, we are able to implement and experiment with the methods we review in Chapter 3.

Answering sub question, A of research question 3:

"How do the methods fit in TKF's situation and what are the criteria for selecting a simulation model?"

We provide an approach to fit the methods in TKF's situation through a simulation model. This allows us to test TKF's situation without altering the real-life situation. Additionally, literature motivates to test their methods in a simulation model as well.

Next, we answer sub question B:

"How can a simulation model be structured for the methods to be applied to TKF's situation?"

To represent reality as closely as possible to understand the full extent of the impact of the methods, we chose input based on gathered data by TKF and define the input carefully in a simulation model.

Additionally, to be able to measure the simulation's representative value, we validated and verified it as well as providing the complete logic behind it. This also includes assumptions and simplifications. With all these components, we have structured an approach to apply the methods to TKF's situation and measure them.

We perform the application of the methods in Chapter 5.

5. Simulation Model Results

This chapter starts with the discussion of the experimental design in Section 5.1, where we highlight the different experiments, we perform. Following that, Section 5.2 provides, discusses and compares the output we gather using the experiments with the simulation model.

5.1 Experimental Design

Table 9 presents the different experiments linked to the approach and parameters we change to execute the approach of them, next to the objectives for what information we aim to gain.

Experiment	Objectives	Approach in DES Model
Baseline Configuration	• Measuring impact of increase in machine speed • Setting the baseline values for the output to compare the other experiments to	• Doubling the production speed of sheathing machine line 6 • Measuring *AWT, TA* & *AVT*
Theory of Constraints	• Identifying new constraint • Measuring improvement of exploiting new constraint • Measuring improvement of subordinating process	• Analyse baseline experiment output • Implement work division from constraining machine line • Pace process with the constraining machine line • Measuring *AWT* for comparison
Drum-Buffer-Rope	• Measuring improvement of installing WIP buffers • Measuring improvement of rope component	• Implement buffers based on WIP restriction • Only assigning work to constraints when there is capacity • Measuring *AWT, TA* & *AVT* for comparison
Kanban	• Reinstalling TKF's WIP level restriction in new situation per step	• Renew reel capacity values at each square • Measuring *AWT* & *TA*
CONWIP	• Reinstalling TKF's WIP level restriction in new situation globally	• Constantly evaluate global average WIP level and adjust inflow of articles accordingly • Measuring *AWT* & *TA*

Table 9: Experiments with Objectives and Approach

Section 5.1.1 describes the baseline configuration experiment of the simulation model with its output, we separate the discussion of this output from the output of the other experiments as we structure those experiments based on the output of the baseline configuration experiment. Afterwards, Section 5.1.2 presents the configuration of the second experiment using TOC methodology. Following the TOC approach, Section 5.1.3 implements the DBR methodology to continue the TOC experiment. Section 5.1.4 continues with the fourth experiment using a Kanban approach after which Section 5.1.5 uses the CONWIP approach in the fifth experiment.

5.1.1 Baseline Configuration & Output

To reach the goal of analysing TKF's situation using the simulation model, we implement the change they are expecting that will adjust their process flow. This change is the increase of production speed of sheathing machine line 6, which will go from 80 m/s to 160m/s. This means that processing times are halved on average for all articles on the machine line which gives the situation we want to test, we implement this rule in the logic of the flowchart in Section 4.2.3.

The output values we experiment for are the average waiting time (*AWT*) per buffer in front of each machine line, total articles (*TA*) produced measured against the number of steps they have performed, and average article throughput time (*AVT*) also measured against the number of steps performed. 'Steps Performed' refers to the number of process steps an article has performed in its production process through the installation department, the number of steps depends on its production path (Chapter 4), for *AVT* and *TA* we keep steps performed into account to provide an accurate representation of which kind of articles are affected most by our interventions. *AWT* is in close relation to the total throughput time of an article, in this simulation model an article's processing times are constant, so only waiting times before processing influence the throughput time. Table 10 represents the outcomes of our baseline configuration experiment with regards to *AWT*, Tables 11 and 12 present *TA* and *AVT*, respectively. We compare to these values and try to improve them in the experiments in the following sections.

Reel Square Machine Line	Ins3	Ins4	Ins5	Str3	Str5	DT3	Sht5	Sht10	Sht8	Brd	Arm1
AWT	51:44	3:03:48	3:05:12	59:56	2:02:20	1:28:32	2:16:16	15:23	39:43	1:12:35	8:19:57

Table 10: Output Baseline Average Waiting Time per Article/CoreCable per Reel Square. (hh:mm:ss)

Steps Performed	1	2	3	4	5
TA	129	227	68	11	-

Table 11: Output Baseline Total Articles Produced with Steps Performed

Steps Performed	1	2	3	4	5
AVT	12:39:23	21:14:43	38:57:55	63:30:34	-

Table 12: Output Baseline Average Article Throughput Time

5.1.2 TOC Experiment

We apply the TOC method we propose in Chapter 3 in this second experiment to start analysing the adjusted process flow. We start with performing the 5 key TOC steps; considering Section 5.1.1, we see that armouring 1 has the highest *AWT*. However, considering the considerably smaller portion of articles that have armouring in their production path and the fact that armouring is soon considered outside of the department, we do not include this in our constraint identification.

Shifting the attention, when analysing utilisation figures in Chapters 2 & 4, utilisation rates were not considerably higher than at other machine lines in the new situation. However, we see the *AWT* at Ins4 and Ins5 are the only ones above 3 hours, making these insulation lines the constraint in this context and for the experiments. The production of core cables is assigned to an insulation line based on what core cables are needed to serve as components of an article going through the stranding step. When an article consists of 5 core cables, it will send more production orders for core cables to the insulation line than if the article would consist of 4 or less core cables. This factor causes the insulation lines that produce the type of core cables used in articles consisting of more core cables to be overloaded more quickly.

After the identification step, we exploit the constraint by dividing the work more equally over the insulation lines. In Chapter 4, we discussed that Ins3 and Ins5 can process the same thickness of core cables so by dividing some core cable production volume to Ins3 from Ins5, we attempt to exploit the constraint. This division of production was not done in the situation before the sheathing line 10 implementation as we see the core cables each have a designated machine line for production in the data we use in Chapter 4.

The division is done in the logic of the flowchart in Section 4.2.3, when the number of core cables waiting for production in the reel square in front of Ins5 is more than 3, the core cables are assigned to Ins3. An article can have a maximum of 5 core cables in this model, which occurs consistently in our data. The capacity of insulation reel squares is 8, meaning 3 is the maximum amount of core cables in the queue that would allow every type of article to have all its core cables assigned, this leads to less blockage with articles that wait for a portion of their core cable production to still be assigned. This means the core cables originally having the Ins5 destination now change that destination Ins3, when the capacity is not large enough. We cannot do this for Ins4, as it produces cables with a different thickness.

For this reason, when we continue with the steps of TOC, we look at subordination as we also perform other interventions to the constraining machine lines in the following sections. The subordination step is similar to what we do for the DBR experiment, thus we test two approaches for this. Subordination to this machine line helps to create a more equal inflow of core cable production orders. To achieve subordination, we structure the other machine lines to operate at a slower pace, to lower the inflow to Ins4. We put this in place by lowering the number of new articles/core cables that enter the other machine lines. We do this by providing a time of 15 minutes of waiting for an article/core cable at each reel square in front of the machine lines in the installation department, except the reel squares in front of the insulation machine lines. We solely measure AWT for this experiment.

5.1.3 DBR Experiment

We implement DBR theory in this experiment by taking the same constraint we determined in Section 5.1.2, which are two of the insulation machines. We use the DBR methodology to schedule workflow based on the constraint in order to improving operations. We perform this in close relation with the steps TOC already takes. When considering the insulation machine lines, we treat Ins4 and Ins5 as the constraints and divide work of Ins5 to Ins3 after which we subordinate the rest of the process to Ins4.

The next step we take involves the three components of DBR. We define the drum as the insulation machine line group as a whole which will dictate the process scheduling of the whole process around it. This means we still consider insulation lines 4 and 5 to be the constraining machine lines as we determine them to be constraining in Section 5.2 when we discuss TOC output. We include Ins3 as well in the drum as we divided work from Ins5 to Ins3 and because assignment of core cable production orders for the insulation machine lines are structured the same way for each machine line.

The buffer component is important for the DBR experiment, we place a buffer of WIP in front of all insulation machine lines as the utilisation is quite low on all Insulation machines compared to the AWT they put out.

The buffer of WIP is within the requirements set by TKF, namely, to have 24 – 48 hours of WIP in front of machine lines, especially the maximum is important when applying DBR. To prevent the WIP levels to overflow this restriction we consider the average processing and setup times Chapter 2 discusses for insulation machine lines. We see that the reel buffers in front of Ins3, Ins4 and Ins5 should have a WIP level of 17-35, 12-23, 13-26 core cables respectively, to comply with the 24-48 hours of WIP ruling. For example, we calculate this for this for the upper WIP level of Ins3 as:

$$Upper\ WIP\ Level = \frac{48 * 60}{81.5} = 35.33$$

We apply the rope element as the largest experimental factor in the DBR experiment. The rope allows us to pace the following of the process to the drum's pacing. In our case, this means the stranding lines should send work (see logic flowcharts Chapter 4) in a more balanced way. We pace the stranding machines down by assigning articles to them only when the insulation lines also have capacity in their reel squares for core cable production orders to be assigned. For this experiment, we measure TA and AVT in addition to AWT.

5.1.4 Kanban Experiment

When we implement the Kanban methodology, we do not utilise any steps we performed in the TOC or DBR methodology, as the aim is to evaluate WIP levels separately from the adjusted flow analysis, for which we select Kanban and CONWIP methodologies. This means, in contrary to the DBR experiment, we start again from the baseline configuration with experiments.

TKF's strategy to place 24-48 hours' worth of WIP in front of each machine line gives us incentive to apply a kanban strategy to the situation. Using Kanban, we simply implement TKF's strategy once more, but in the new situation. We find a distinction between the Kanban approach for this and the CONWIP approach to achieve TKF's strategy in Section 5.1.4, namely that with Kanban we specify for each process step/machine line specifically what the WIP levels should be and with CONWIP we control it globally.

To implement the Kanban approach, when an article is assigned to move to its next destination in the simulation model after entering or performing a step, we no longer base the possibility of the move on the capacity of the reel squares, but we rather implement a restriction of 24-48 hours of WIP in front of each machine line and add only when the 'machine occupation times' of all the articles in front of a machine added together do not exceed 48 hours. Machine occupation time refers to the time an article spends on processing and setting up on one machine line.

The physical application of Kanban using cards does not occur in a simulation model. However, we utilise the same strategy to comply with the WIP restrictions. When an article performed a production step in the simulation model and waits to be assigned to the next step, we check the maximum level as described above. So outside of the simulation model, when the maximum level is not reached, a card or space is available on the reel square until it is filled again to 48 hours.

For the minimum of 24 hours, we use the logic that articles will continuously be assigned to the reel square until a maximum of 48 hours of WIP is reached and that the articles in the reel squares all have high occupation rates in the baseline configuration output, except for the armouring line. Looking at process steps, this 24-hour level is reached continuously so with the Kanban strategy we look primarily at restricting it to the maximum of 48 hours of WIP.

5.1.5 CONWIP Experiment

Similarly to the Kanban approach in Section 5.1.3, we again look at the 24-48 hours of WIP in front of each machine line rule. To implement this in the new situation, CONWIP takes a more global approach, differing from the Kanban approach. The CONWIP also starts again from the baseline configuration.

To achieve the desired effect of the CONWIP approach, we limit total maximum WIP for the whole department. Still, this is a WIP level of 24-48 hours, but we take it as an average value, as the study in Chapter 3 implements as well. We achieve this by taking all WIP levels of the reel squares in the simulation model and dividing that by the number of reel squares, giving us the average occupation of those reel squares defined in hours of WIP.

We increase arrival intensity when the WIP level is below 24 hours until that lower limit is reached and we do not let article production orders flow into the model until when the WIP level is 48 hours, or if that will be 48 hours or more when the article would flow into the model. This method guarantees the maximum level of WIP is never exceeded.

5.2 Output Experiments

Section 5.2.1 presents all output values we gather from the simulation model in each experiment. Section 5.2.2 then discusses these values.

5.2.1 Output Values

Table 13 shows the output values of all experiments we conduct in Section 5.1 with regards to *AWT*, except the output of the baseline configuration experiment.

		Reel Square Machine Line										
		Ins3	Ins4	Ins5	Str3	Str5	DT3	Sht5	Sht10	Sht8	Brd	Arm1
Experiments	Base Line	51:44	3:03:48	3:05:12	59:56	2:02:20	1:28:32	2:16:16	15:23	39:43	1:12:35	8:19:57
	TOC (First)	53:01	3:04:02	2:33:52	54:34	1:51:41	1:20:29	2:19:22	15:31	40:16	1:15:23	8:26:57
	TOC (Second)	1:05:55	3:00:02	2:44:40	57:17	2:09:54	1:22:12	2:09:24	16:28	40:15	1:21:30	6:35:06
	DBR	41:30	2:29:52	2:22:39	42:25	34:52	1:34:07	54:20	11:18	22:29	42:56	5:53:56
	Kanban	52:55	2:34:41	2:53:19	1:47:12	2:49:08	2:22:45	1:25:02	14:03	31:39	1:21:30	7:14:25
	CONWIP	46:25	2:43:36	2:51:34	28:17	40:28	52:28	1:43:53	31:19	58:32	1:49:25	4:30:21

Table 13: Output Experiments Average Waiting Time per Article/CoreCable per Reel Square (hh:mm:ss)

Table 14 presents output values of all experiments where we measure *TA*.

		Steps Performed				
		1	2	3	4	5
Experiments	Base Line	129	227	68	11	-
	DBR	111	241	69	10	1
	Kanban	108	236	67	19	0
	CONWIP	156	263	58	10	0

Table 14: Output Experiments Total Article Produced with Steps

Table 15 presents the output values for *AVT*, which we only measure for the DBR experiment.

Steps Performed	1	2	3	4	5
Baseline	12:39:23	21:14:43	38:57:55	63:30:34	-
AVT	10:50:47	22:45:35	38:48:16	83:40:33	33:18:21*

Table 15: Output DBR Average Article Throughput Time (hh:mm:ss) (= only one article with 5)*

5.2.2 Output Discussion

First, we consider the output of TOC regarding *AWT* in Table 13. We see that by exploiting the constraint, the *AWT* of the core cables in front of Ins5 decreases, while the *AWT* in front of Ins3 barely increases. By increasing the use of this tactic of dividing the work more equally where possible on the insulation machines, we approach a first solution to solving this constraint.

Next, we consider the values we gather for the second experiment described in Section 5.1.2 for TOC; we see that the *AWT* in front of insulation 4 decreases very slightly and for other process steps, *AWT* increases. The decrease of production pace of the other machines does not seem to have a large positive effect on this situation, also when decreasing their pace more intensively. Therefore, the subordination step of TOC does not add much value when added to the constraint exploiting step.

Moving on to the results of DBR, we compare the values to the output of the baseline configuration and TOC experiments. We see, considering the insulation lines on their own, a decrease in average waiting times on reel squares. Additionally, at machine lines Str3, Str5, Sht5, Sht8 and Brd we see a drastic decrease in *AWT*. This could be seen as a positive effect, however as most machines decrease significantly in *AWT*, we interpret this as an effect of less articles being allowed to flow through the system using our strategy, leaving the machine lines to be less occupied and process their waiting lines quicker, which results in a lower *AWT*.

However, when we compare *TA* of the baseline output with DBR output, the observed values do not differ significantly. Only the value for articles that performed only one step in their production process have a larger difference in this comparison. We explain this as follows; a large portion of the time, a stranding machine is the one destination of an article that only performs one step in its production process. When the article performs this step, a core cable production order is sent. This means the articles only performing one step are impacted the most by the DBR experiment, as a larger relative portion of the articles flowing through the system have to 'wait' because of the rope installed than with the other types of articles performing more steps.

However, for the other types of articles, we see that with 4 steps performed, the *AVT* increases significantly as the chance is high that an article performing 4 steps has to perform the stranding step first and thus assigning core cable production orders which creates the possibility of having to 'wait' as well.

Using this reasoning, we determine the DBR strategy and especially its rope component seem to impact the rest of the process steps negatively, while not improving *AWT* for the insulation lines thus not improving the constraint. However, when the strategy for implementing the rope is made less drastic, we can observe a positive effect on the constraint while still allowing the rest of the process to perform as closely to the situation before. This can be done by allowing stranding machines to send core cable production orders even when insulation lines do not have full capacity of all necessary core cables of an article, instead of the strategy we used now.

The buffer we install, increases the average waiting time on a reel square per article, however due to the great impact of the rope and less core cables to be assigned, we do not see a representation of this in Table 14. Utilisation rates of the insulation lines do go up using this strategy.

After discussing the output of the adjusted process flows analysis methods, we discuss the WIP evaluation methods, starting with Kanban. For this method, we observe increased *AWT* for most machine lines compared to the baseline configuration, especially the stranding machines and sheathing 5. The latter occurs a lot in article paths, compared to the other sheathing machines, explaining the fact it is more affected by a change like increasing articles that can go there, compared to the normal setup. This is what happened using the Kanban approach.

Considering the insulation machine lines, we can see *AWT* went up slightly for Ins3 but down for the other two. This means the constraining factors we identify in Section 5.1.1 are benefitted by this setup. As the stranding lines are dependent on the production performance at the insulation line, naturally *AWT* went up, as now more articles are assigned in front of the stranding lines, even if their core cable components have not completed production.

Lastly, output values for *TA* show that the one step article production number went down. As we note above for the DBR output, this is a direct result of the stranding lines strongly reoccurring in the path of a one destination article, where more waiting time is created and thus less article can be treated. In general, *TA* went down slightly.

When comparing this output to the Kanban experiment and the baseline output, we see some differences. We consider the insulation lines first, where *AWT* has been decreased in comparison to the baseline output, but not as significantly as the Kanban approach did. However, the Kanban had a notable increase in *AWT* at the stranding lines compared to the baseline, the CONWIP approach did not have this effect and even decreased the values significantly.

As a result of this, the one step articles were produced more as they were able to flow to their one machine, without the obstruction of hours of WIP as with the Kanban approach. Through the CONWIP approach, the imbalance the Kanban approach creates for these articles was solved and even improved.

The global approach allows WIP levels to be higher where needed. Two of the points we propose in Chapter 3 was that the CONWIP approach has a lower maximum of WIP needed and throughput increases. These are features we proved in this experiment.

5.3 Conclusion

In this chapter, we discussed research question 4:

"How does the constructed analysis of the adjusted process flow and evaluation of WIP levels perform in the situation with the new sheathing line?"

We approach the answer to this question with the use of two sub questions, the first of which is:

"How do the new WIP evaluation and adjusted flow analysis compare to the current situation?"

The output of the baseline configuration confirms TKF's expectations and motivations for this research. The new sheathing line has a relative high performance and creates a vacuum in the process, shifting the bottleneck elsewhere. *AWT* at the new sheathing line is low compared to the other machine lines and its utilisation goes down compared to the data in Chapter 2. We determine a strong change in the process flow compared to Chapter 2.

Next, we look at sub question B:

"What output do the methods provide?"

To answer this question and get the output, we introduced 5 different experiments, with the 1st being based on identifying and exploiting the constraint using TOC methodology. From the output results, we deducted that using our strategy of dividing work between constraining machine lines (insulation) we decreased *AWT* by 32 minutes while not increasing *AWT* at the insulation line that got more work through that strategy. Next, the experiment with the TOC step involving subordination did not result in large decreases of *AWT* at machine lines, for the constraining machines the positive effect of the first TOC experiment was decreased with 11 minutes.

The 3rd experiment continued with the structure of the TOC experiments and used DBR methodology. There we saw a strong decrease in *AWT* at various machine lines, Ins3, Ins4 and Ins5 all saw a significant decrease compared to the baseline and TOC experiments. However, we linked this to the fact fewer articles flow through the system in the strategy we applied. This strategy involved introducing the three components of DBR. Especially articles performing one step were impacted. The rope component of DBR negatively affected other non-constraining process steps, while not significantly improving the situation of the constraining process steps.

We continued with WIP methodology in the 4th and 5th experiments using Kanban and CONWIP theories respectively. Kanban increased *AWT* for most machine lines, particularly for stranding and sheathing machine lines where it went up with in between 45 minutes and an hour. *AWT* did go down for some insulation machines but up for Ins3 with only a minute. Congestion at stranding was increased which significantly impacted one-step articles. CONWIP performed better than Kanban. *AWT* was significantly reduced at the stranding lines, which avoided the imbalance the Kanban approach did create. For example, Str3 saw a decrease of 31 minutes, where Str5 had a decrease of 1 hour and 20 minutes. More one-step articles were produced.

6. Conclusion & Advice

This chapter concludes the report by answering all research question in Section 6.1 and by forming advice and recommendations from that for TKF in Section 6.2.

6.1 Conclusion

We present a short recap of the results gathered in our research approach for answering the main research question:

"What is the impact of implementing a new sheathing line at TKF's installation department cable production process on required WIP levels and the process flow?"

The goal of this research was to analyse the impact of the implementation of a new, high-speed sheathing line at TKF in terms of the process flow and a re-evaluation of WIP levels. To reach this goal and to answer the main research question, we divided the research in parts to answer different sub research questions.

First, we analysed the current situation in Chapter 2, with this we approached research question 1:

"What does the current situation look like with regards to process flow/production planning?

The production process layout in the current situation consists of multiple groups of machines. Every group has a function dedicated to one out of five steps in the production process. Reel squares function as spaces to store WIP and provide input to the machine lines. In this situation, they also determine the amount of WIP until there is overcapacity. A product can follow a wide variety of paths through the layout, depending on its specific production process. The current sheathing line has a utilisation of 90,34%, which is high compared to other machine lines. The sheathing line will be swapped for a new version which will be able to pull a cable through at twice the speed and is expected to eliminate the bottleneck TKF observed before.

Chapter 3 answered research question 2:

"What planning methods for analysing adjusted process flows and WIP level evaluation in production processes are known in literature?"

For analysing adjusted process flows, we chose to explore TOC and DBR methodology which focus on the identifying and managing bottlenecks/constraints. TOC plays a larger role in identifying and exploiting the constraint and also incorporates improvement of the constraint. DBR synchronises the process around the constraint with its three key departments. We use this to analyse the adjusted process flow and provide clarity of where constraints are positioned. To evaluate WIP levels, we selected Kanban and CONWIP. We can use the methods to restrict WIP. Kanban limits WIP at each process step specifically, while CONWIP sets limits for the entire process.

Next, research question 3 was answered in Chapter 4:

"In what structure can the methods be applied to fit into the situation of this research at TKF?"

We chose to utilise a simulation model; this was already done in studies we reviewed in Chapter 3 and it provides an appropriate way of implementing our methods and testing interventions without making any real adjustments to the real-life situation. We made assumptions and simplifications, after which we verify and validate the simulation model to give the appropriate and representative structure to apply and test the methods. Using a warm-up period of 105 days and a number of replications of 20, we get rid of initialisation bias, and we get results from the simulation model that have high accuracy.

Chapter 5 provided the experimental design and output of the methods when we implemented them in the simulation model, with that it answered research question 4:

"How does the constructed analysis of the adjusted process flow and evaluation of WIP levels perform in the situation with the new sheathing line?"

The baseline configuration experiment, where we create the new situation with the doubled production speed of the sheathing line, results in output that aligns with TKF's expectations for the research and shifting the bottleneck to other parts of the process. Its utilisation also decreases compared to earlier data in Chapter 2, indicating a significant change in process flow and the relocation of constraints as a result of the new sheathing line's efficiency. Sheathing line 10 results in an *AWT* of 15 minutes which is way lower than most other machines.

After the baseline configuration, we used the first TOC step to identify the constraint in the new situation. We determined this to be insulation line 4 with a high *AWT* of 3 hours and 3 minutes, as well as insulation line 5 with an *AWT* of 3 hours and 5 minutes. Next, the second TOC step was where we exploit the constraint. We do this by dividing work from insulation line 5 to insulation line 3, as they are both able to manage the same type of thickness of the core cables. This strategy results in a decrease in *AWT* at insulation line 5, which was now 1 hour and 51 minutes. There was a slight increase in *AWT* at insulation line 3, from 51 minutes to now 53 minutes. After exploitation, we subordinated the rest of the process to the biggest remaining constraint which was insulation line 4. This subordination resulted in large increases in *AWT*, for example at stranding line 5 where it increases from 1 hour and 51 minutes to now 2 hours and 9 minutes. In general, the TOC methodology allowed us to identify the new situation's constraint and exploiting it resulted in an improvement, subordination did not.

After the TOC experiments, we used DBR methodology to pace the process around the constraint, which thus functioned as the drum, we made use of WIP buffers and implemented the 24–48-hour restriction set by TKF for the WIP level. This meant the reel buffers of the insulation lines should have a WIP level of 17-35, 12-23, 13-26 core cables for insulation lines 3, 4 and 5 respectively. Lastly, the rope component allowed the rest of the process to alter its speed to the drum. In the DBR experiment we saw a decrease in *AWT* at all insulation lines, going from 1 hour and five minutes to 41 minutes for insulation line 3, from 3 hours to 2 hours and 29 minutes for insulation line 4 and from 2 hours and 44 minutes to 2 hours and 22 minutes for insulation line 5. At other machine line we also saw a drastic decrease in *AWT*. However, this is explained by the fact that the rope component led to less articles being allowed to flow through the production process and *TA* was less high when compared to the baseline configuration output. The rope component can still be used, but in a less impactful way by altering the strategy.

Moving on to WIP evaluation, we aimed to put back in place TKF's WIP level restriction. The first experiment using Kanban methodology was structured by limiting the movement of an article depending on the capacity of a reel square. When the capacity would be at or go over 48 hours, the article would wait to flow to its destination until the capacity was large enough.

This was specified per machine line. The Kanban experiment resulted in an increase of *AWT*, especially for the stranding machines and sheathing 5, the latter saw an increase from 2 hours and 16 minutes to 2 hours and 49 minutes. These machines occur in a lot of production paths, explaining the fact they are more affected by a change and this strategy caused more articles to flow to those machines. *AWT* went up slightly for insulation line 3 but the constraining insulation lines 4 and 5 saw a decrease, from 3 hours and 3 minutes to 2 hours and 34 minutes for insulation line 4 and from 3 hours and 5 minutes to 2 hours and 53 minutes for insulation line 5. Especially for insulation line 4 this is an improvement. The strategy resulted in a congestion at the stranding lines, causing their *AWT* to go up. This congestion eventually led to less *TA*, in the baseline configuration this was 435 and this became 430 with the Kanban strategy.

The CONWIP experiment involved the same objective as Kanban, but we restricted WIP levels globally by calculating the average amount of WIP in hours of all reel squares combined. When this value falls below 24 hours, arrival intensity of articles was increased and when it is 48 hours or will be 48 hours when an article enters the system, the arrival of articles is restricted. The results we gathered showed again a decrease in *AWT* at the insulation lines, but not as significantly as with Kanban. The CONWIP approach did however also not have a drastic increase of *AWT* at the stranding lines where for example stranding line 5 went from 2 hours and 2 minutes to now 52 minutes. As a result of this improved efficiency, the articles containing stranding machine lines in their production paths were produced more and *TA* increased from 435 to 487. With these results we determine CONWIP is more appropriate to implement TKF's WIP restriction in the new situation compared to Kanban.

In general, we saw from the baseline configuration experiment that the bottleneck in the process shifts from the sheathing group to the insulation group. Continuing, the two TOC experiments delivered a reduction in *AWT* when we redistribute work amongst the insulation group, when possible. This is an approach that is considerable. From the DBR experiment we see that synchronising to the constraining machine reduces *AWT*, this is a good part, however the rope component negatively impacts the production cell's performance. The DBR methodology is however considerable when the rope component is adjusted. From the two WIP methodologies, we learn that implementing CONWIP will give more favourable results.

6.2 Recommendations & Limitations

We present recommendations to TKF after conducting this research in Section 6.2.1, in Section 6.2.2 we offer limitations of this research that should be considered. Section 6.2.3 discusses motivation for further research.

6.2.1 Recommendations

We provide several recommendations to TKF and its installation department.

The theory of constraints is a tool TKF should continuously use apart from the experiments we perform in Chapter 5. Those experiments did not have a positive impact entirely; however the methodology TOC provides should be applied. The only true way to stabilise the adjusted process flow is to repeat the process TOC provides with its 5 key steps, the frequency of this repetition should be based on when the process is changed like with a new machine line, way of planning or other adjustment. It can also be put in place on a monthly basis, when this is found appropriate. Bottlenecks in the process might shift and implementing this ruling will help to identify them in time to improve them before they can adversely impact the company.

After the impact of the new machine line is properly analysed painting a complete picture of the new situation, TKF should implement the CONWIP ruling more favourably compared to Kanban to revise WIP levels across the production process. Additionally, applying CONWIP in reality using its card strategy is regarded simpler than to apply Kanban to its full extent.

After implementation of the new sheathing line, we recommend TKF to measure the true output the implementation provides. Afterwards, such research could be conducted again to get a grip on the true, real-life outcomes. Again, continuously conducting some form of analysis helps to create an up-to-date overview. Different approaches should be taken where for example an OEE factor can be implemented. With different approaches, it is easier to create a representative analysis.

6.2.2 Limitations

As we conducted our research and implemented methods using a simulation model, we were bound to the borders of the simulation application. Simplifications of the real-life situation were put in place, as well as components left out to increase measurability. Therefore, this research considers an optimal situation, where the process flows as expected.

Implementing methods into a simulation model has less of an impact than implementing in reality. This is why this research lacks taking into account the risk factor of methods not working as expected.

6.2.3 Further Research

Further research on this topic could include a larger simulation model, to more accurately display the situation. Additionally, different WIP strategies can still be considered, like for example dynamic WIP control. In this research, we took the machine performance as a constant, the impact of an adjustment to a process can become more detailed when fluctuating machine performance is taken into account. A completely different way to approach a research project like this is with the use of industry 4.0 technologies.

Appendices

First, Appendix A provides an extended cause-effect cluster as we reference to in Chapter 1. Appendix B discusses the stakeholders we consider during this research. Appendix C provides full page versions of both the floor plan as well as the production paths of the current situation. Afterwards, Appendix D shows a picture of a cable reel as used at TKF. Appendix E continues with a description of the sheathing process. After that, Appendix F discusses the data preparation we conduct. Appendix G provides auxiliary information to motivate decisions of the simulation model. Finally, Appendix H presents the bibliography.

Appendix A. Extended Cause-Effect Cluster

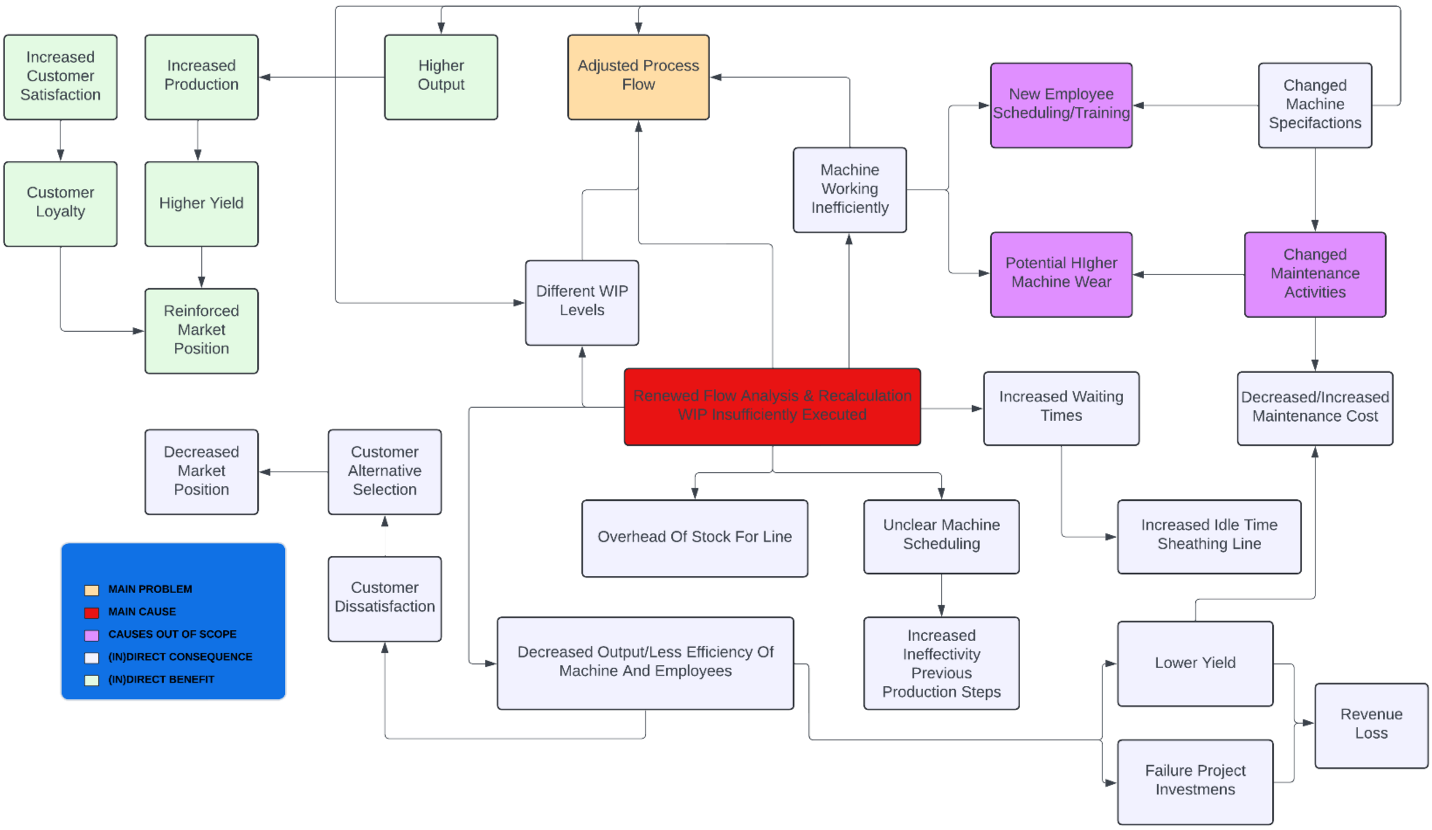


Figure 17: Extended Cause-Effect Cluster

Appendix B. Organisational Stakeholders

Stakeholders within the context of this research are individuals that are impacted, and more importantly influence the decisions that are made while conducting the research. These stakeholders are the individuals, organisation or other groups that are affected by the conduction of this research, or that are dependent on the outcomes to decide their future situation. Stakeholders can come from any layer of the organisation of TKF and are classified according to the importance/interest matrix shown in figure 18.

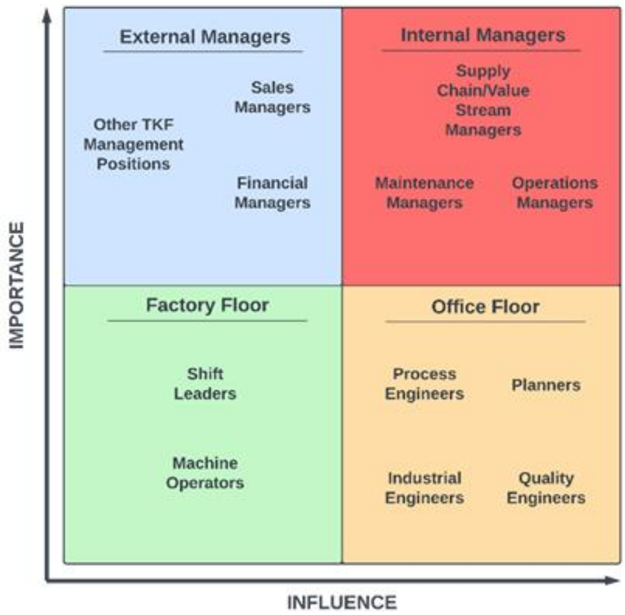


Figure 18: Stakeholder Analysis

In Figure 18, the importance axis signifies the power a stakeholder has within decision making with regards to the topic of this research. The influence axis depicts how much they are influenced by the decisions that are made. Generally, the influence axis shows to what degree a stakeholder is involved with the research topic.

Starting at factory floor in the installation department, shift leaders and machine operators are impacted slightly, but are not noticeably influenced due to decision making with regards to this research as their work will be altered slightly but the main process steps will remain to be the same. The shift leader manages machine operators and has more power in decisions, as they discuss with the office floor extensively about everyday operations and provide good insight about what requirements are.

Moving on to office floor, these are the stakeholders who look from the outside on the process while still being in contact with the stakeholders on the factory floor. They analyse problems or opportunities in the department and generate ideas for decision making, they are thus highly influenced by this research as it is part of their portfolio to work with the results of it. Their importance is not as high as with the managers, but they do highly influence the decisions of managers as well as they are the ones generating motivation for decisions and executing them.

External managers provide input for the department, like the sales managers generating production orders, but they are low on the influence scale. They are not directly influenced by the outcomes of this research as it does not change a working process for them. They also work with the output of the department and the stakeholders on the office floor, for example with delivery dates that change or grouping of orders for effectivity of the production flow. Their importance is high in their position, as their work does influence the whole department and this research.

Lastly, the managers that look at operational aspects in the department are highly influenced and also highly important in decision making. They keep the overview over the production process and collaborate with each other group in the process of decision making. They are influenced by this research in a way where the outcomes will change their outlook on the production process, and they have to alter their decision making to that as well.

Appendix C. Full Page Versions Floor Plan & Production Paths

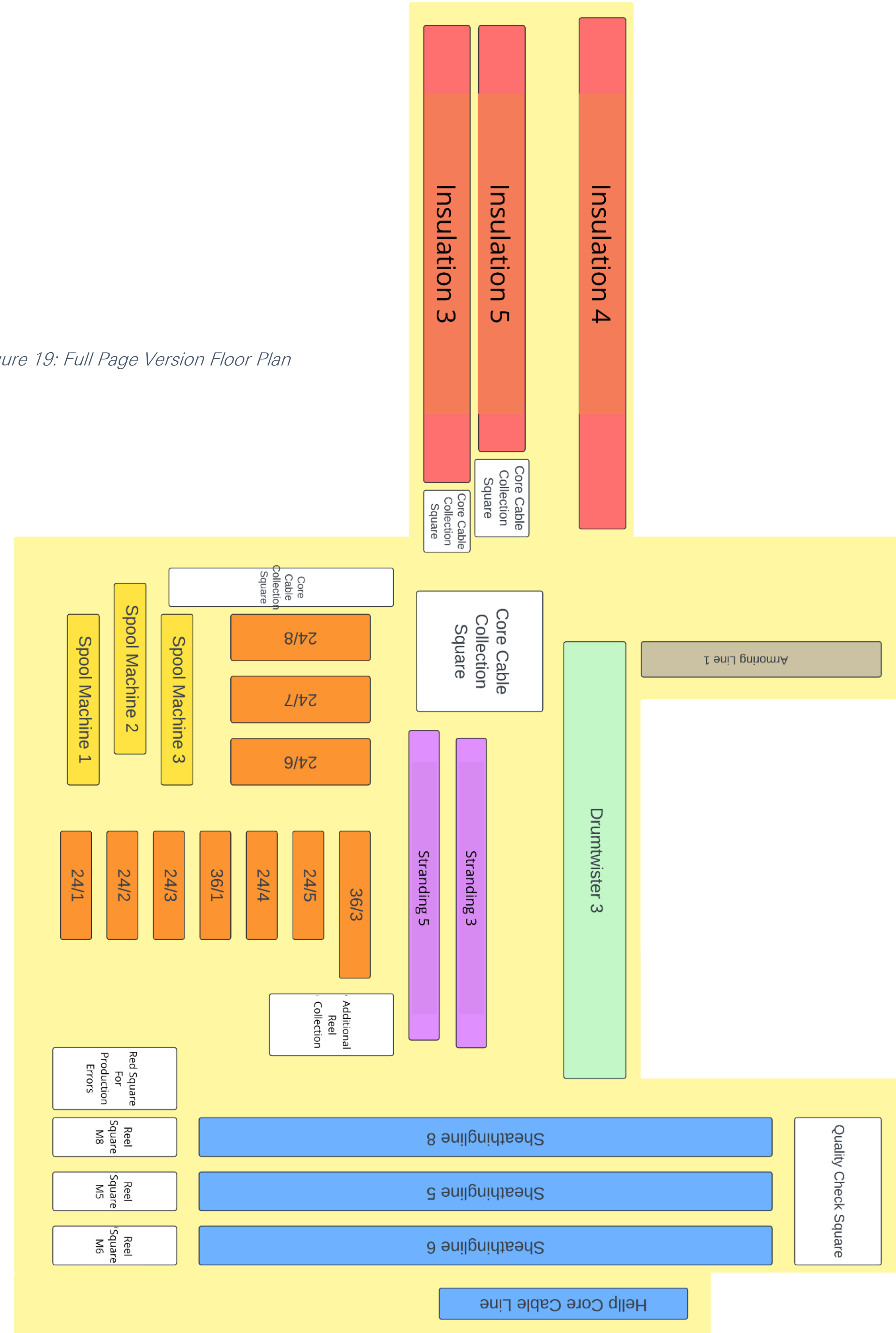


Figure 19: Full Page Version Floor Plan

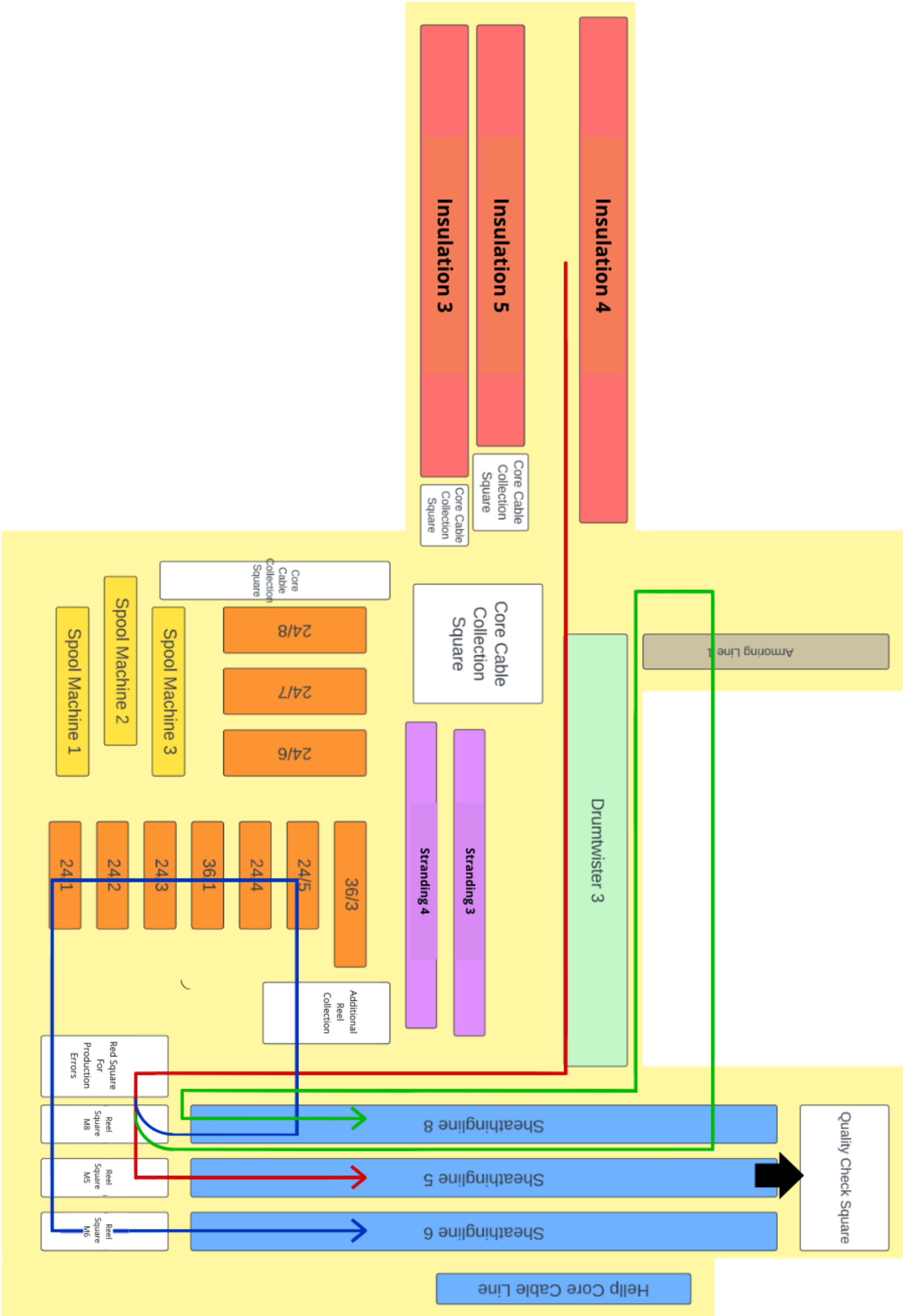
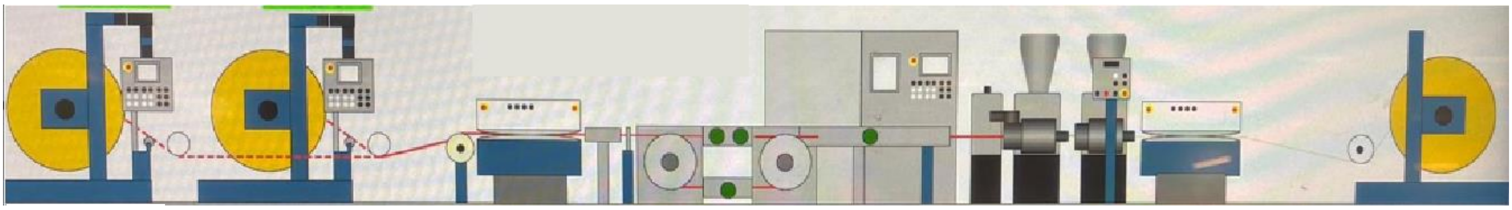


Figure 20: Full Page Version Floor Plan with Production Paths

Appendix D. Cable Reel Used at TKF

Figure 21: Cable Reel Used at TKF

Appendix E. Sheathing Line Process Steps & Materials Used



12 11 6 5 4 3 2 1

Figure 22: Sheathing Process Steps

We specify the sheathing steps according to the figure above and the numbers below Not all steps are represented in this schematic depiction of the sheathing line, but it gives a general idea of how it is constructed.

In Section 2.1.1, the first definition of the sheathing line looks into the global activities performed by that machine. Depending on the production path of an order, an inner or outer sheath is applied to the cable. The sheath consists of a plastic coating made out of MBZH, PVC or XPLE materials. There are different steps within the machine line which are numbered.

1. Cable Unwinding Frame: *Lets the cable go of the reel that is carrying, it allows the cable to enter the sheathing line.*
2. Tension Wheel: *Creates tension in the cable/wire that is being produced, this prevents tangling and unequal sheath application in a later stage in the sheathing process.*
3. Preheater: *The cable is heated as a preparation before entering the next step.*
4. Extruder: *The plastic material is melted and mixed and applied around the cable.*
5. Crosshead: *Shapes the material around the cable and makes sure the cable becomes smooth again.*
6. Cooling Trough: *Cools the cable back down after sheath is applied.*
7. Diameter Gauge: *Measures through the cable to ensure diameter consistency and ensures quality of the product.*
8. Capstan: *Moves the cable through the machine at a constant speed so it can go through all the production steps.*
9. Accumulator: *Temporary cable storage to ensure changes in processes downstream do not influence the rest of the process.*
10. Spark Tester: *Testing of cable insulation integrity.*
11. Printer: *After producing an outer sheath, the cable is printed with required product specifications.*
12. Collecting Machine: *Collecting the cable that finished the sheathing process step on a reel again.*

The sheathing process either involves putting an inner sheath on the semi-finished product or an outer sheath on a product that is the end product after the sheathing production step. An inner sheath is provided on cables with armouring or braiding to protect the cable's structure from the iron or copper components that are applied during those steps.

The materials for input in the sheathing line are the semi-finished product coming from earlier steps in the production process, and the type of sheath that is applied. As mentioned above, the sheath consists of either MBZH, PVC or PE.

- MBZH: The abbreviation stands for '*Moeilijk Brandbaar Zonder Halogeen*' meaning the material has low flammability and contains no halogen, this increases the safety aspect of the final product, and it means that less hazardous substances are released in case of a fire.
- PVC: The abbreviation stands for 'Polyvinyl Chloride', this material is most standardly used as a sheathing material and contains halogen and has less capacity for warmth than MBZH.
- PE: The abbreviation stands for '*Polyethylene*', this material is not widely used in the installation department but can occur sporadically.

Figure 23: MBZH Material

Appendix F. Data Preparation

For the simulation model provided in Chapter 4, this section describes the way the data for input is retrieved (Section 7.6.1) and filtered (Section 7.6.2). Afterwards, in Section 7.6.3, VBA Coding assists in filtering the data more thorough and finding inconsistencies. Finally, Section 7.6.4 reveals the way the data is presented to look into specific values, when needed.

Appendix F.1 Data Retrieval

Taking 2 years' worth of data for the installation department, a representative input for the simulation model is provided. This data is taken on various criteria from TKF's ERP system Navision. These criteria are department, production number, production order number, notification date and time, article number, variant, description one and two, produced length, processing steps, setup time and lastly processing time. These different indicators are useful in describing the current situation in Chapter 2 as well as providing a good basis for data preparation to extract the correct values.

Appendix F.2 Table Filters

Using the pivot table property in Excel, we filter lists of data according to preferred values. Table 16 gives an example, the names of machines, setup times averages and processing time averages are presented in Dutch, which is the language of choice for TKF's data collection. When we convert the data to the TPS simulation model, we translate all relevant identifiers to English.

Bew. plaatsnr.	**Average of Insteltijd**	**Average of Bewerkingstijd**
EI ARMEERLIJN 1	90,10369147	332,2055588
EI DRUMTWISTER 3	98,83429967	106,960249
EI ISOLATIELIJN 3	26,33543334	55,18945216
EI ISOLATIELIJN 4	43,44414851	78,18948365
EI ISOLATIELIJN 5	23,26824616	86,00396233
EI MANTELLIJN 5	15,7777415	76,99483269
EI MANTELLIJN 6	23,49990868	65,73246842
EI MANTELLIJN 8	12,66329397	89,15315996
EI SAMENSLAGLIJN 3	26,33624561	150,2267868
EI SAMENSLAGLIJN 4	31,5	10,5
EI SAMENSLAGLIJN 5	35,88386752	123,6651061
EI VLECHTER 24-1	12,69074231	507,1003885
EI VLECHTER 24-2	56,39575333	852,9122
EI VLECHTER 24-4	40,50033794	1052,568791
EI VLECHTER 24-5	6,726315789	294,3697421
EI VLECHTER 24-6	29,63514888	1244,474979
EI VLECHTER 24-7	68,7771	353,2051
EI VLECHTER 36-1	37,94431866	819,5648084
EI VLECHTER 36-3	41,16122353	862,1973118
Grand Total	**27,6656532**	**151,7132132**

Table 16: Filtered Table for Setup Time & Processing Time

We alter a pivot table like we show in the example by switching what column or row values are shown. Averages, sums and counts are features to analyse the data further. To narrow down the dataset for each type of data that is necessary, pivot tables are used to initially filter for the necessary variables.

Appendix F.3 VBA Coding

After we copy data to generate relevant output, VBA coding helps to further filter the data where necessary. Below figures and steps represent each VBA code manipulation used to filter data for a given purpose.

1. Connect Process Steps to Article Number

In Figure 23, we present the code we use to filter the data where the article number has different production steps connected to it, they were however not assigned to the article number and could only visually be linked. To connect them, this code assigns the article number to each production step that belongs to that number.

```
Sub CheckIfCellsAreEmpty()
    Dim ws As Worksheet
    Dim row As Integer
    Dim value As Integer
    Dim nextrow1 As Integer
    Dim nextrow2 As Integer
    Dim nextrow3 As Integer

    Dim cellValue As Variant

    ' Set the worksheet
    Set ws = Worksheets("Sheet1")

    ' Loop through cells


    For row = 2 To 10934
        nextrow1 = row + 1 'set each row to check, up to 4 rows maximum
        nextrow2 = row + 2
        nextrow3 = row + 3
        If IsEmpty(ws.Cells(row, 2)) Then 'check for each of the rows under the non empty row if it is empty, if so write article number.
            If IsEmpty(ws.Cells(nextrow1, 2)) Then
                If IsEmpty(ws.Cells(nextrow2, 2)) Then
                    If IsEmpty(ws.Cells(nextrow3, 2)) Then
                    ws.Cells(nextrow3, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(nextrow2, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(nextrow1, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(row, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(row - 1, 1).value = ws.Cells(row - 1, 1).value
                    Else
                    ws.Cells(nextrow2, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(nextrow1, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(row, 1).value = ws.Cells(row - 1, 1).value
                    ws.Cells(row - 1, 1).value = ws.Cells(row - 1, 1).value
                    End If
                Else
                ws.Cells(nextrow1, 1).value = ws.Cells(row - 1, 1).value
                ws.Cells(row, 1).value = ws.Cells(row - 1, 1).value
                ws.Cells(row - 1, 1).value = ws.Cells(row - 1, 1).value
                End If
            End If
            ws.Cells(row, 1).value = ws.Cells(row - 1, 1).value
            ws.Cells(row - 1, 1).value = ws.Cells(row - 1, 1).value
        End If
    Next row

End Sub
```

Figure 24: Connecting Process Steps to Article Number.

2. Filter Order Numbers

In order to filter out order numbers from a large dataset, which is in this case the order numbers where core cables are produced, this code provides a way to only keep the order data of the main products. We use the code to divide the order numbers in core cables and main products.

```vba
Sub FilterOrdersNumbers()
    Dim Orders(1 To 659) As Long
    Dim x As Integer
    Dim y As Long
    Dim z As Integer


        For x = 1 To 659    'store ordernumbers
            Orders(x) = Worksheets("Sheet7").Cells(x, 1).value
        Next x

    For y = 10934 To 1 Step -1
        For z = 1 To 659
        If Worksheets("Sheet14").Cells(y, 2).value = Orders(z) Then 'check if an order number is in a row, if so clear contents
            Worksheets("Sheet14").Rows(y).ClearContents
        End If
        Next z
    Next y

End Sub
```

Figure 25: Filters Out Core Cable Order Numbers

3. Lining Up Article Paths

```vba
Sub LiningUpMachinePaths()
    Dim wsSource As Worksheet
    Dim wsDestinationFull As Worksheet
    Dim wsDestinationEmpty As Worksheet
    Dim lastRow As Long
    Dim destRowFull As Long
    Dim destRowEmpty As Long
    Dim i As Long
    Dim j As Long
    Dim emptyCount As Long


    Set wsSource = ThisWorkbook.Sheets("Sheet17") 'make short reference to sheets to simplify syntax
    Set wsDestinationFull = ThisWorkbook.Sheets("Sheet18")
    Set wsDestinationEmpty = ThisWorkbook.Sheets("Sheet19")


    destRowFull = 1 'initialising row check values


    destRowEmpty = 1


    lastRow = 9752 'last row that needs to be checked


    For i = 1 To lastRow

        emptyCount = 0 'counts how many cells are empty
       ' Check if the current cell is empty
        If wsSource.Cells(i, 1).value = "" Then
            ' Skip to the next cell if the current cell is empty
            GoTo ContinueLoop
        End If
        ' Counts the number of consecutive empty cells below the current cell
        For j = i + 1 To WorksheetFunction.Min(i + 4, lastRow)
            If wsSource.Cells(j, 1).value = "" Then
                emptyCount = emptyCount + 1
            Else
                Exit For
            End If
        Next j

        ' Checks the number of empty cells is up to 4
        If emptyCount <= 4 Then

            If emptyCount = 0 Then
                ' Copy the values from the current cell and the two adjacent columns to wsDestinationFull
                wsDestinationFull.Cells(destRowFull, 1).value = wsSource.Cells(i, 1).value 'this puts the path in the columns next to the article number, easy to copy
                wsDestinationFull.Cells(destRowFull, 2).value = wsSource.Cells(i, 2).value
                wsDestinationFull.Cells(destRowFull, 3).value = wsSource.Cells(i, 3).value

                ' Update the destination row counter
                destRowFull = destRowFull + 1
            Else
                ' Copy the values from the current cell and the two adjacent columns to wsDestinationEmpty
                wsDestinationEmpty.Cells(destRowEmpty, 1).value = wsSource.Cells(i, 1).value
                wsDestinationEmpty.Cells(destRowEmpty, 2).value = wsSource.Cells(i, 2).value
                wsDestinationEmpty.Cells(destRowEmpty, 3).value = wsSource.Cells(i, 3).value

                ' Copy the values of empty cells in the same columns
                For j = 1 To emptyCount
                    wsDestinationEmpty.Cells(destRowEmpty + j, 1).value = wsSource.Cells(i + j, 1).value
                    wsDestinationEmpty.Cells(destRowEmpty + j, 2).value = wsSource.Cells(i + j, 2).value
                    wsDestinationEmpty.Cells(destRowEmpty + j, 3).value = wsSource.Cells(i + j, 3).value
                Next j

                ' Update the destination row counter
                destRowEmpty = destRowEmpty + emptyCount + 1
            End If
        End If
ContinueLoop:
    Next i
End Sub
```

Figure 26: Lining Up Articles with Paths

Next, the main products that go through multiple production steps in the installation department have their article number connected to it as number 1 in this section proposes. Now to use this data in the simulation model, we gather the steps in connection to the respective article numbers to be able to have the possible paths set out for each article while keeping in mind multiple paths can be possible for some articles. We show this in Figure 26 and 27.

```
Sub CopyCellsIfBelowNotBlank()
    Dim wsSource As Worksheet
    Dim wsDestination As Worksheet
    Dim lastRow As Long
    Dim destRow As Long
    Dim i As Long


    Set wsSource = ThisWorkbook.Sheets("Sheet17")
    Set wsDestination = ThisWorkbook.Sheets("Sheet18")


    destRow = 1


    lastRow = 9208

    ' Loop through each cell
    For i = 1 To lastRow
        '
       If wsSource.Cells(i, 1).value = "" Then
       GoTo ContinueLoop
       End If
        If wsSource.Cells(i + 1, 1).value <> "" Then

            wsDestination.Cells(destRow, 1).value = wsSource.Cells(i, 1).value 'if the cell is not blank, the values are copied to the other sheet
            wsDestination.Cells(destRow, 2).value = wsSource.Cells(i, 2).value
            wsDestination.Cells(destRow, 3).value = wsSource.Cells(i, 3).value

            destRow = destRow + 1
        End If
ContinueLoop:
    Next i


End Sub
```

Figure 27: Lining Up Articles with Paths

4. Translate Machine Names

As most variables in the TKF data are given in Dutch, this code effectively translates each case in Figures 28 and 29.

```
Sub ChangeNamesV2()
Dim wsSource As Worksheet
Dim i As Long
    Set wsSource = ThisWorkbook.Sheets("Sheet9")
        For i = 1 To 550

        If wsSource.Cells(i, 3) = "EI SAMENSLAGLIJN 3" Then
        wsSource.Cells(i, 3) = "Stranding3"

        ElseIf wsSource.Cells(i, 3) = "EI SAMENSLAGLIJN 5" Then
        wsSource.Cells(i, 3) = "Stranding5"

        ElseIf wsSource.Cells(i, 3) = "EI DRUMTWISTER 3" Then
        wsSource.Cells(i, 3) = "Drumtwister3"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-1" Then
        wsSource.Cells(i, 3) = "Braiding241"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-2" Then
        wsSource.Cells(i, 3) = "Braiding242"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-3" Then
        wsSource.Cells(i, 3) = "Braiding243"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-4" Then
        wsSource.Cells(i, 3) = "Braiding244"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-5" Then
        wsSource.Cells(i, 3) = "Braiding245"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-6" Then
        wsSource.Cells(i, 3) = "Braiding246"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-7" Then
        wsSource.Cells(i, 3) = "Braiding247"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 24-8" Then
        wsSource.Cells(i, 3) = "Braiding248"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 36-1" Then
        wsSource.Cells(i, 3) = "Braiding361"

        ElseIf wsSource.Cells(i, 3) = "EI VLECHTER 36-3" Then
        wsSource.Cells(i, 3) = "Braiding363"

        ElseIf wsSource.Cells(i, 3) = "EI MANTELLIJN 5" Then
        wsSource.Cells(i, 3) = "Sheathing5"

        ElseIf wsSource.Cells(i, 3) = "EI MANTELLIJN 6" Then
        wsSource.Cells(i, 3) = "Sheathing6"

        ElseIf wsSource.Cells(i, 3) = "EI MANTELLIJN 7" Then
        wsSource.Rows(i).delete

        ElseIf wsSource.Cells(i, 3) = "EI MANTELLIJN 8" Then

        ElseIf wsSource.Cells(i, 3) = "EI ARMEERLIJN 1" Then
        wsSource.Cells(i, 3) = "Armouring1"

End If
Next i
End Sub
```

Figure 28: Translating Dutch to English

```
Sub CoreCablesNames()
Dim i As Long

For i = 2 To 459
    If ThisWorkbook.Sheets("Sheet49").Cells(i, 3) <> 0 Then
        ThisWorkbook.Sheets("Sheet49").Cells(i, 9) = "Insulation3"
    ElseIf ThisWorkbook.Sheets("Sheet49").Cells(i, 5) <> 0 Then
        ThisWorkbook.Sheets("Sheet49").Cells(i, 9) = "Insulation4"
    ElseIf ThisWorkbook.Sheets("Sheet49").Cells(i, 7) <> 0 Then
        ThisWorkbook.Sheets("Sheet49").Cells(i, 9) = "Insulation5"
    End If
Next i
End Sub
```

Figure 29: Translating Dutch to English

5. Article Separation

In this data preparation, we separate the articles in one step or multi step classes. The code in Figure 30 separates the one step products from the ones with multiple steps. This assists the creation of appropriate data sets to later divide the arrival procedure of these articles in the simulation model.

```
Sub filter4Times()

Dim i As Long
Dim j As Long
Dim Row2Check As Long
Dim Row3Check As Long
Dim Row4Check As Long

Dim m As Long
Dim ArticleNr(1 To 620)

For i = 1 To 619
    ArticleNr(i) = ThisWorkbook.Sheets("Sheet14").Cells(i + 1, 1) 'puts all relevant article numbers in the array
Next i

m = 1
Row2Check = 1393


ContinueLoopV4:

Do While Row2Check > 1

    If ThisWorkbook.Sheets("Sheet32").Cells(Row2Check, 1).value = ArticleNr(m) And m < 620 Then 'checks if cell value corresponds with the article number

        m = 1 'nothing changes and goes to next row

            Row2Check = Row2Check - 1

        GoTo ContinueLoopV4

    ElseIf ThisWorkbook.Sheets("Sheet32").Cells(Row2Check, 1).value <> ArticleNr(m) And m < 620 Then

        m = m + 1  'articleNr not yet found so goes over all the different article numbers
        GoTo ContinueLoopV4

    ElseIf m = 620 Then
        ThisWorkbook.Sheets("Sheet32").Rows(Row2Check).EntireRow.delete 'corresponding article number not found, so the row is deleted, it is not suitabl
        m = 1
            Row2Check = Row2Check - 1
        GoTo ContinueLoopV4

    End If
Loop
End Sub
```

```
Sub FilterTimes()
Dim i As Integer
Dim j As Long

Dim ArticleNr(620 To 756)

For i = 620 To 756
        ArticleNr(i) = ThisWorkbook.Sheets("Sheet13").Cells(i - 619, 1)
Next i

For j = 2 To 1393
    For i = 620 To 756
        If ThisWorkbook.Sheets("Sheet36").Cells(j, 2) = ArticleNr(i) Then
            ThisWorkbook.Sheets("Sheet36").Cells(j, 1) = i
        End If
    Next i
Next j
End Sub
```

Figure 30: Filter Out Irrelevant Article Numbers

6. One Step Article Filter

The following code takes the one step article class and goes over duplicates, in the data set the processing at the one specific process step the article performs is noted multiple times. Therefore, the data can be logically filtered according to analysing if it occurs multiple times or not in Figure 31.

```
Sub ArticleOnePathDest()
Dim i As Long
Dim j As Long
Dim m As Long

Dim NumberStore(1 To 137)
Dim RowStore(1 To 137)
For j = 1 To 137
    NumberStore(j) = ThisWorkbook.Sheets("Sheet13").Cells(j, 1)
    RowStore(j) = 0
Next j

i = 502
ContinueLoop:
i = i - 1
Do While i > 1
For m = 1 To 137
    If ThisWorkbook.Sheets("Sheet28").Cells(i, 1) = NumberStore(m) And RowStore(m) = 0 Then

        RowStore(m) = 1


        GoTo ContinueLoop

    ElseIf ThisWorkbook.Sheets("Sheet28").Cells(i, 1) <> NumberStore(m) And m < 138 Then

        GoTo ContinueLoop2

    ElseIf ThisWorkbook.Sheets("Sheet28").Cells(i, 1) = NumberStore(m) And RowStore(m) = 1 Then

        ThisWorkbook.Sheets("Sheet28").Rows(i).EntireRow.delete


    GoTo ContinueLoop
   Else
    GoTo ContinueLoop:

    End If

ContinueLoop2:
Next m
Loop

End Sub
```

Figure 31: One Step Article Filter

7. One Step Processing Times

For the main articles, we filter the pivot table on the main article numbers and connect it to all processing steps these articles possibly perform. Thereafter, we determine the setup times and processing times for each machine for the simulation model. For the articles only performing one step, a different approach is necessary, below the code only provides the processing time/setup time for the relevant processing step the respective articles perform.

```
Sub CreateTimes()
Dim i As Long
Dim j As Long

Dim ws As Worksheet

Set ws = ThisWorkbook.Sheets("Sheet36")

For i = 2 To 138
        If ws.Cells(i, 14) = "Stranding5" Then
        ws.Cells(i, 12) = ws.Cells(i, 13)
        ElseIf ws.Cells(i, 14) = "Drumtwister3" Then
        ws.Cells(i, 4) = ws.Cells(i, 13)

        ElseIf ws.Cells(i, 14) = "Stranding3" Then
        ws.Cells(i, 11) = ws.Cells(i, 13)

        ElseIf ws.Cells(i, 14) = "Sheathing5" Then
        ws.Cells(i, 8) = ws.Cells(i, 13)

        ElseIf ws.Cells(i, 14) = "Sheathing6" Then
        ws.Cells(i, 9) = ws.Cells(i, 13)

        ElseIf ws.Cells(i, 14) = "Sheathing8" Then
        ws.Cells(i, 10) = ws.Cells(i, 13)

        ElseIf ws.Cells(i, 14) = "Armouring1" Then
        ws.Cells(i, 3) = ws.Cells(i, 13)

        End If
    Next i
    End Sub
```

Figure 32: One Step Processing Times

8. Grouping & Copying Braiding Times

The braiding machines have averages for the processing/setup times that do not vary much when taken over the whole portfolio of TKF. Chapter 4 explains the way that fact is taken for simplifying the model. In the data preparation, for each article that does some type of braiding step, we adjust the processing/setup time to a global average for one article and grouped together under one variable depending on the machine.

```
Sub BraidingTimes()
Dim i As Long
Dim j As Long


For i = 1 To 3636
    For j = 3 To 7
        If ThisWorkbook.Sheets("Sheet37").Cells(i, j) = "Braiding" Then
            ThisWorkbook.Sheets("Sheet37").Cells(i, 8) = "748.2991651"
        End If
    Next j
Next i
End Sub
```

```
Sub BraidingTimes2()
Dim m As Long
Dim n As Long
Dim l As Long


Dim NrStore(1 To 619)


m = 3638
ContinueLoop:
m = m - 1
Do While m > 1
    For n = 619 To 1 Step -1
        If ThisWorkbook.Sheets("Sheet37").Cells(m, 1) = n And NrStore(n) = 0 Then
            NrStore(n) = 1
            GoTo ContinueLoop
        ElseIf ThisWorkbook.Sheets("Sheet37").Cells(m, 1) = n And NrStore(n) = 1 Then
        ThisWorkbook.Sheets("Sheet37").Rows(m).EntireRow.delete
        GoTo ContinueLoop
        End If
    Next n
Loop
End Sub
```

Figure 33: Grouping & Copying Global Average Times

9. Copying Setup Times

The following code filters the article setup times for the machines with only one destination processing step. We consequently label them, and they can then be filtered on. That way we are able to filter over the processing times with the setup times.

```
Sub FilterSetupTimes()
Dim i As Long
Dim j As Long
Dim k As Long

Dim NrSetupTimes(620 To 756)

For i = 620 To 756
    NrSetupTimes(i) = ThisWorkbook.Sheets("Sheet43").Cells(i - 619, 2)
Next i

For j = 2 To 1373
    For k = 620 To 756
        If ThisWorkbook.Sheets("Sheet42").Cells(j, 2) = NrSetupTimes(k) Then
            ThisWorkbook.Sheets("Sheet42").Cells(j, 1) = "10"
        End If
    Next k
Next j
End Sub
```

Figure 34: Filter & Copy Times for Setup

Appendix F.4 End Data Results

To present the prepared datasets in an orderly manner and to create opportunity for further data manipulation, if necessary, we offer an Excel spreadsheet. Figure 35 shows the front page of this spreadsheet, where the different datasets can be found. In the spreadsheet this front page serves as the location to navigate to each sheet.

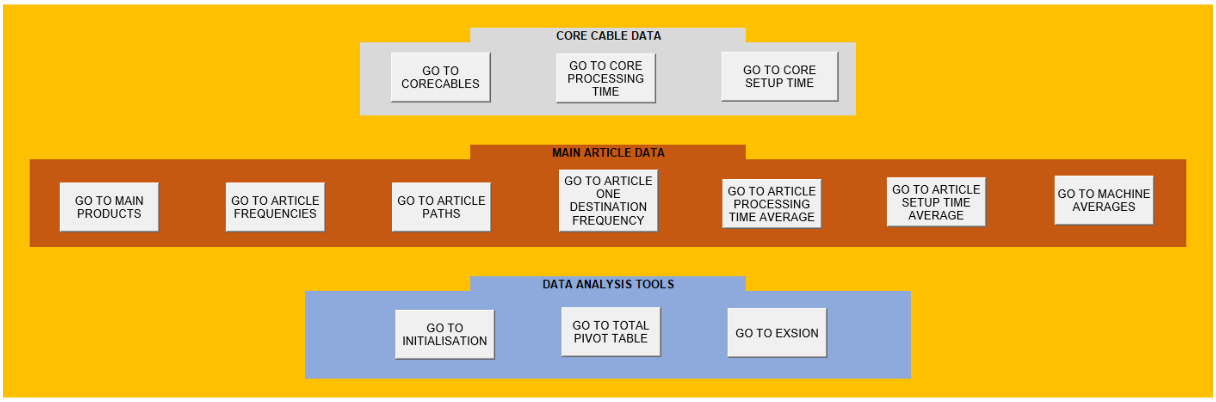


Figure 35: Front Page Data Collection Spreadsheet

Appendix G. Simulation Model Auxiliary Information

This section contains auxiliary information about the construction of the simulation model we present in Chapter 4. Section 7.5.1 motivates the decision made for the application that is used to construct the simulation model and gives the application's key features. Section 7.5.2 presents the installation department laid out in the simulation model, presenting the basis of the flow of articles through the system, as Chapter 4 describes. Section 7.5.3 shows the interface of the simulation model with coding objects and tables. Section 7.5.4 provides a bigger version of one of the logic flowcharts from Chapter 4. After that, Section 7.5.5 provides an overview of the functionality of different objects of the simulation model. Lastly, Section 7.5.6 provides the approach with which we determined the warm-up period and number of replications needed for the simulation model.

Appendix G.1 Modelling Application Decision

Comparing the simulation for the current situation of this research, we see that the different techniques all have advantages and disadvantages for possible applications. For now, we consider applications able to treat DES simulations as this are relevant in this research. Different applications with their advantages and disadvantages for DES simulation:

Table 17: Simulation Modelling Applications

Application	Advantages	Disadvantages
FlexSim	• 3D Imaging • Activity Dashboard • Data Representation • Stochasticity • Motion Modelling	• Not UT Licensed
Simio	• 3D imaging • Stochasticity • Change Management • Real Time Data	• Not UT Licensed
SolidWorks Simulation	• Physical Object Manipulation • Motion Modelling • Stochasticity	• No 3D Imaging • Not UT Licensed
Tecnomatix Plant Simulation by Siemens (TPS)	• 3D Imaging • Stochasticity • Dashboard • Data Verification • UT Licensed	• Less Modern • No Motion Modelling

From Table 22 allows interpretation that these top applications serve different purposes, where FlexSim takes on a lot of visualisation, Simio is more focused on change management and can utilise real time data, SolidWorks takes an approach where physical objects play a larger role and lastly, Tecnomatix is more of a hybrid program and also UT licensed.

Reviewing each of the options in Table 21, the decision falls onto Tecnomatix Plant Simulation (TPS). This model provides the necessary possibilities regarding what problems and situations it can be used for. Comparing to the other applications, only FlexSim offers a similar perspective on simulation and would be highly usable for this research as well. However, considering the University of Twente offers licensed usage for TPS and not for FlexSim, the decision is to use TPS.

Additionally, this decision for TPS was discussed with parties at TKF, who agreed to judge this application as adequate for simulating their problem and providing the right incentive for the generation of further recommendations and findings in this research.

This application uses several terms to denote elements in a simulation model. A short glossary of terms is given to highlight the most important cases of terms in Table 23.

Table 18: Tecnomatix Plant Siemens Terms

TPS Term	Meaning
(Mobile) Unit	An object that flows through the model and each process step.
Method	A tab to write code to construct the model.
Source	Location of inflow of mobile units.
Drain	Location of outflow of mobile units
Buffer	An instance able to store mobile units.
Sorter	An instance able to direct mobile units
Assembly Station (Production Step)	An instance able to process a unit.

Appendix G.2 Installation Department Layout in Plant Simulation

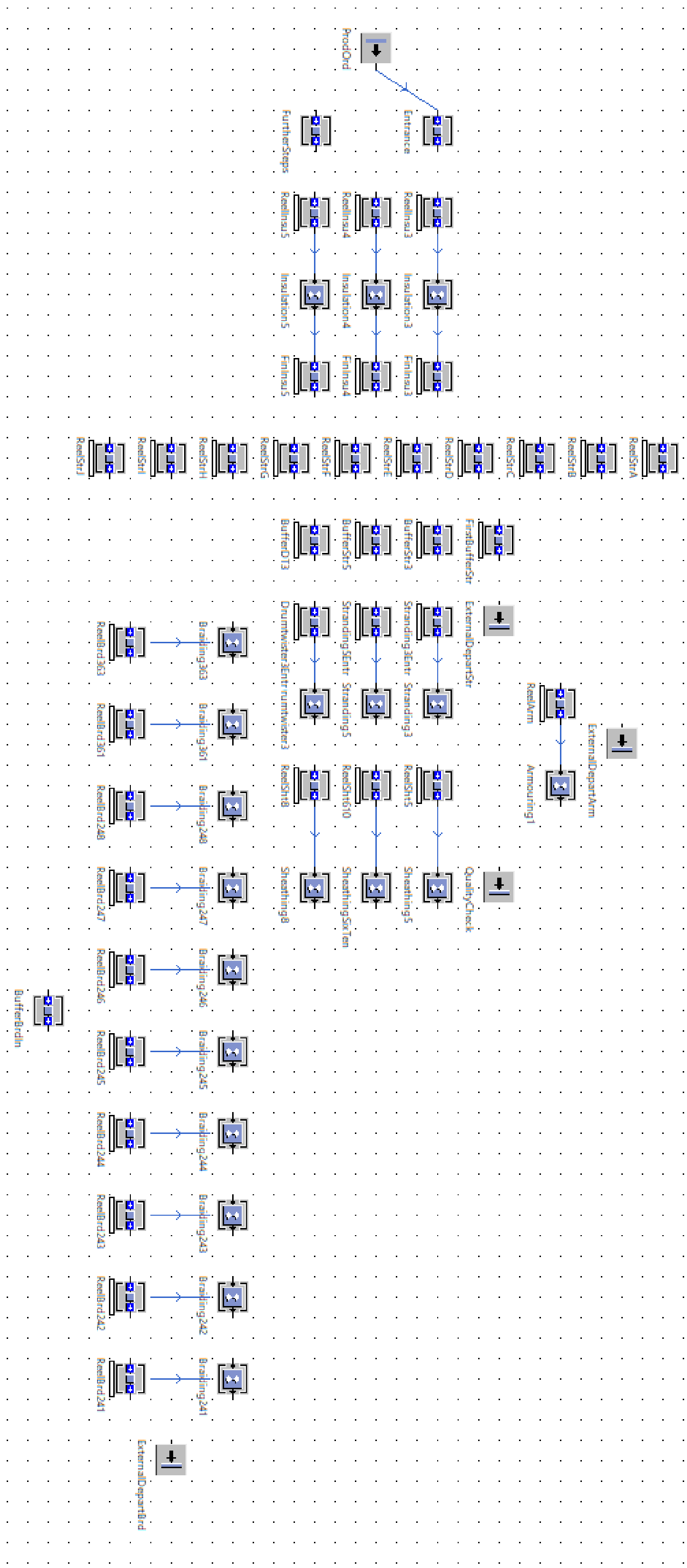


Figure 36: Installation Department Layout in Plant Simulation

Appendix G.3 Interface Simulation Model

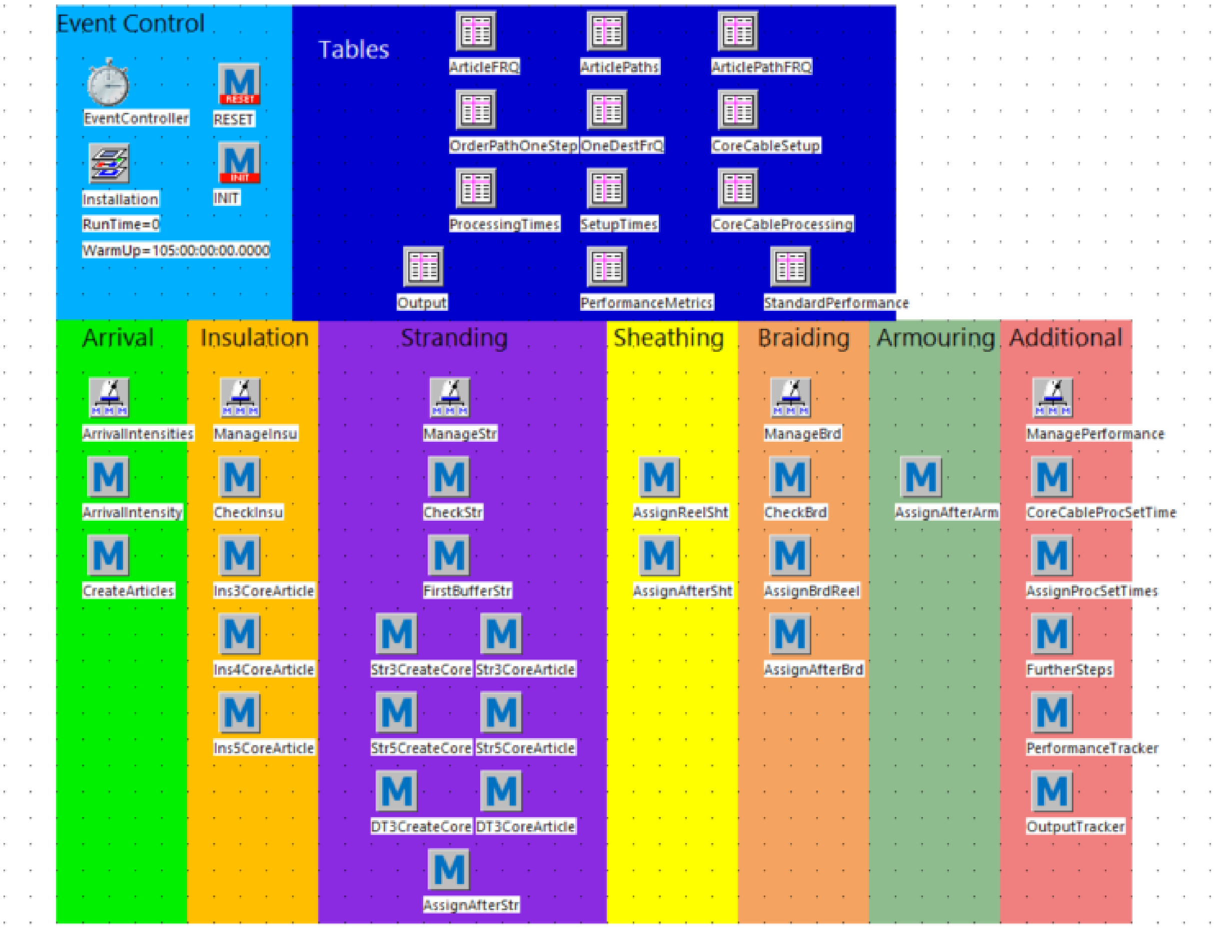


Figure 37: Interface Simulation Model

Appendix G.4 Larger Version Flowchart 4.2.3

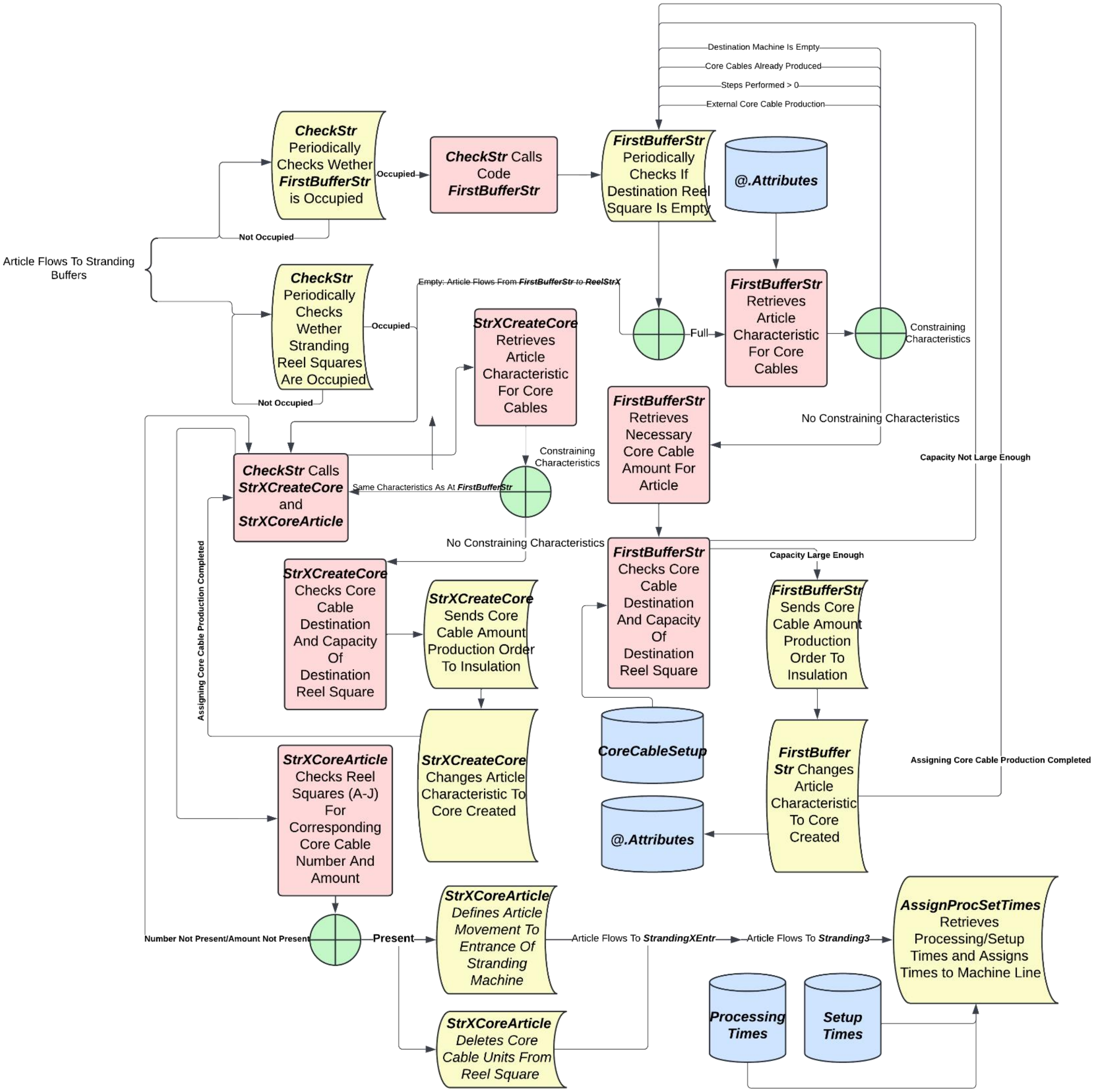


Figure 38: Larger Version of Assigning Core Cables & Stranding Step (StrX = Str3, Str5 or DT3)

Appendix G.5 Simulation Model Objects Functionality

Generators	Objective
ArrivalIntensities	- Calls *ArrivalIntensity* at the start of each day
ManageInsu	- Calls *CheckInsu* periodically - Prevents infinite loops without the use of generators
ManageStr	- Calls *CheckStr* periodically - Prevents infinite loops without the use of generators
ManageBrd	- Calls *CheckBrd* periodically - Prevents infinite loops without the use of generators
Methods	**Objective**
ArrivalIntensity	- Assigns a different arrival intensity for article on each new day
CreateArticles	- Picks one destination type article or multiple destination type article - Weighted pick for exact type of article, based on its occurrences in the two-year data. - Weighted pick for the path of the article, based on their occurrences in the two-year data
CheckInsu	- Checks if there are core cable units in the insulation machines and calls *Ins3CoreArticle*, *Ins4CoreArticle* and *Ins5CoreArticle* if they contain a unit
Ins3CoreArticle, Ins4CoreArticle, Ins5CoreArticle	- Assigns core cables to stack until they reach the right number for a main article to be produced at the stranding step. - Check what reel square (a-j) already contains the same article number for core cables and sends it there if so
CheckStr	- Checks if there are article units in either *FirstBufferStr, BufferStr3, BufferStr5 or BufferDT3* and calls *FirstBufferStr*, *Str3CreateCore* and *Str3CoreArticle*, *Str5CreateCore* and *Str5CoreArticle* and *DT3CreateCore* and *DT3CoreArticle* respectively, in case they are occupied.
FirstBufferStr	- Manages the assignment of core cable production orders to the insulation machines, even when stranding machines are occupied and thus the main articles waiting in line do not send these orders from there
Str3CreateCore, Str5CreateCore, DT3CreateCore	- Manages the assignment of core cables when main article with its first step at stranding arrives at the buffer
Str3CoreArticle, Str5CoreArticle, DT3CoreArticle	- Checks when all necessary core cables are present in designated reel square, then moves the main article to the stranding machines and subsequently deletes the core cable units

AssignAfterStr, *AssignAfterSht,* *AssignAfterArm,* *AssignAfterBrd,* *FurtherSteps*	- Checks next destination for article and assigns it
AssignReelSht	- Checks the right destination for incoming sheathing production orders
CheckBrd	- Checks if there are article units in *BufferBrdIn* and calls *AssignBrdReel* when this is the case
AssignBrdReel	- Assigns braiding production orders to a random open location at the braiding machines and makes sure no blockage is achieved
CoreCableProcSetTime	- Assigns processing/setup time for each core cable in production at the insulation machine lines
AssignProcSetTimes	- Checks location of article and assigns processing and setup times for location production step
Tables	
ArticleFRQ	- Contains the frequency of each article's occurence
ArticlePaths	- Contains the paths each article can take
ArticlePathFRQ	- Contains the frequency of the paths for each article
OrderPathOneStep	- Contains the destination of the articles with only step to perform
OneDestFRQ	- Contains the frequency of the one step articles
CoreCableSetup	- Contains the setup times for each core cable
CoreCableProcessing	- Contains the processing times for each core cable
ProcessingTimes	- Contains the processing times for each article
SetupTimes	- Contains the setup times for each article

Table 19: Method Functionality

Appendix H. Bibliography

Heerkens, H., & Van Winden, A. (2021). Solving managerial problems systematically. In Routledge eBooks. https://doi.org/10.4324/9781003186038

Hopp, W. J., & Roof, M. (1998). Setting WIP levels with statistical throughput control (STC) in CONWIP production lines. *International Journal of Production Research*, *36*(4), 867–882. https://doi.org/10.1080/002075498193435

Winston, W. L. (1991). *Operations research: Applications and Algorithms*. Brooks/Cole.

Rosova, A., Behun, M., Khouri, S., Cehlar, M., Ferencz, V., & Sofranko, M. (2020). Case study: the simulation modeling to improve the efficiency and performance of production process. *Wireless Networks*, *28*(2), 863–872. https://doi.org/10.1007/s11276-020-02341-z

Law, A. M. (2014). *Simulation Modeling and Analysis*. McGraw-Hill Education.

Mayo-Alvarez, L., Del-Aguila-Arcentales, S., Alvarez-Risco, A., Sekar, M. C., Davies, N. M., & Yáñez, J. A. (2024). Innovation by integration of Drum-Buffer-Rope (DBR) method with Scrum-Kanban and use of Monte Carlo simulation for maximizing throughput in agile project management. *Journal Of Open Innovation Technology Market And Complexity*, *10*(1), 100228. https://doi.org/10.1016/j.joitmc.2024.100228

Sundar, R., Balaji, A., & Kumar, R. S. (2014). A Review on Lean Manufacturing Implementation Techniques. *Procedia Engineering*, *97*, 1875–1885. https://doi.org/10.1016/j.proeng.2014.12.341

Pettersen, J., & Segerstedt, A. (2008). Restricted work-in-process: A study of differences between Kanban and CONWIP. *International Journal Of Production Economics*, *118*(1), 199–207. https://doi.org/10.1016/j.ijpe.2008.08.043

Spearman, M. L., Woodruff, D. L., & Hopp, W. J. (1990). CONWIP: a pull alternative to kanban. *International Journal Of Production Research*, *28*(5), 879–894. https://doi.org/10.1080/00207549008942761

Bonney, M.C., Zhang, Z., Head, M.A., Tien, C.C., Barson, R.J., 1999. Are push and pull systems really so different? International Journal of Production Economics 59 (1), 53–64.