Optimizing the Changeover Process for the Production on Jacketing Line 2 at TKF

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Management Summary

The research performed for this thesis assignment was done at Twentsche Kabelfabriek in Lochem. Twentsche Kabelfabriek is a manufacturer of electricity cables, more specifically electricity cables for Wind turbine farms and from generators to neighbourhoods. The company prioritizes the cables for the wind turbine farms as these generate the most profit, and the other cables are produced when machinery is available.

The company currently has congestion on the production line at Jacketing Line 2, this machine needs to put a jacket on all the types of cables that pass through the facility whereas other machines are only used for one cable type. To improve on this congestion Twentsche Kabelfabriek wants to investigate the changeover times between the production processes to see if improvements can be made. To investigate if the changeover time of this machine can be improved a research question is formulated as follows:

"How can Twentsche Kabelfabriek reduce the changeover time of Jacketing Line 2 to address the congestion on the production line of medium voltage cables?"

This research question is tackled using the management problem-solving method, at first the problem was identified which led to the aforementioned research question. After this, the problem approach was formulated where each step to be able to tackle the research question is discussed. Next the problem we analysed the problem, finding the steps of the changeover and when they are currently performed. In this step, we found that Jacketing Line 2 plays a crucial role in the production of subsea and medium voltage cables and that the cables have separate production lines for all other operations on the cable.

Next up we did a literature review on models that apply to changeover schedules. A schedule for the changeover process has multiple requirements, there is a precedence that the activities have to follow for the process to be possible and there is not an endless availability of operators to perform the process. In this literature review we found that a common theory to improve changeover processes, Single-Minute Exchange of Die can not be implemented normally at the company. However, we did find a fitting model, the Resource Constrained Project Scheduling Problem (RCPSP), this model uses the availability of operators and the precedence between the activities to calculate an optimal schedule.

In the next step, we implemented the model following the requirements for a changeover schedule, using this model the availability of operators was compared so that an improved schedule fits the needs of Twentsche Kabelfabriek. For the last step, we evaluate the results of the model and conclude what can be done next. The model results found that on average the changeover duration can be reduced by 38% with a new schedule. This was the case for an availability of 3 and 4 operators, which helps in keeping flexibility for the employees. These new schedules show that important activities currently performed in sequence can be performed simultaneously as well. The schedules also show that it can be beneficial to the total duration of the process to perform one activity later which seems logical to save time for other activities.

In conclusion, we recommend that Twentsche Kabelfabriek implement the new schedules that were calculated by the RCPSP model for the different changeover processes at the company. This way the process only needs to be performed by 3 operators since they can do the process in an equal amount of time to 4 operators. This is done by performing the operations simultaneously and making sure that when the longer activities are not performed after everything else is done. Performing the process like this means the team lead has more flexibility for the other operations in the facility. Next to this, we recommend researching the effectiveness of the implementation of the new schedule. To verify the results from the model we recommend the company to test the processes with 4 operators as well to see if any outside factors influence the performance of the new schedules.

Contents

List of Abbreviations

Abbreviation	Description
TKF	Twentsche Kabelfabriek
MV	Medium Voltage
MPSM	Management problem-solving method
LP	Linear Programming
MILP	Mixed Integer Linear Programming
ERP	Enterprise resource planning
JA2	Jacketing Line 2
SMED	Single-Minute Exchange of Die
JSSP	Job Shop Scheduling Problem
RCPSP	Resource Constrained Project Scheduling Problem

Chapter 1
Methodology

1.1 Company Background

This research will be done at Twentsche Kabelfabriek (TKF) in Lochem. TKF is a manufacturer of electricity cables that has multiple production locations in the Netherlands and around the world. Across all these locations they have around 800 employees. Their cable portfolio consists of subsea cables that are used for offshore wind turbine farms, as well as medium-voltage and high-voltage cables. In their production facilities in Lochem, they make use of high-tech machines like a continuous welding process, this innovative work environment is something they are proud of and strive for.

In 2023 the production of medium voltage cables was started at the production location in Lochem, for this production new equipment was installed. Since space is limited at the facility in Lochem parts of the production are done on a machine that is used for the subsea cables as well, Jacketing line 2. The production of subsea cables has priority on this machine but when this production is finished medium voltage cables are processed. This combined production on the same machine is not fully optimized yet which is why the focus of this research will be on looking at the changeover time of the machine.

1.2 Problem Identification

1.2.1 Action Problem

The market that TKF is operating in has seen an ever-increasing demand due to the congestion on the electricity net in the Netherlands. As said by the Minister of Climate and Energy, in Jetten (2024), more sustainable energy is generated at home and for the network to handle this a lot more cables need to be put into the ground. Next to the energy produced at homes, there are a lot of companies that are on the waitlist to be connected to the grid. As can be seen in the press releases of Alliander (2024) the grid operators are investing a lot of money in the grid to address the congestion. TKF works together with these grid operators to fulfil the demand they have which means that they need to produce a lot of medium voltage cables.

To be able to fulfil the demand for a large number of medium voltage cables, management at TKF wants the production process to be as efficient as possible in producing these cables, something that is not the case at the moment since the facility is not originally designed to produce these cables. To get higher efficiency the process around the double-use machine has to be investigated to see how the output of medium voltage cables can be increased. This leads to the following action problem:

"The output of Medium Voltage cables at Twentsche Kabelfabriek is lower than desired.

1.2.2 Problem Cluster

To tackle the action problem mentioned above, we need to find the underlying problems to see where improvement possibilities lie. To find these problems, we start the research by discussing the current situation with employees at the company. These people know what individual problems are present at the company that can influence our action problem. The problems they brought up are visualized in the problem cluster in Figure 1. The arrows between the problem squares show the causality between the problems, when a problem is closer to the action problem it has a more direct relation to the action problem. In the problem cluster the problems are divided into 4 types, the green box denotes the action problem. A yellow box shows a problem that we can not influence, it may be a requirement from the customer or a decision made by management. A white box is a problem that itself consists of separate problems that can be solved and for the last color, orange, a box shows a potential core problem that can be researched during the research.

In the discussions with employees, three problems were raised that are directly related to the action problem. For our research a problem needs to be influenceable, this is not the case for two of the issues raised. One of these is the quality check, to ensure the safety of the cables and follow regulations TKF needs to check the cable quality, this takes time in the production of cables but removing or decreasing the quality check is not possible. The other problem is the management decision to give priority to subsea cables over medium voltage cables, this decision is made because of the type of orders from customers as well as the facility's configuration of storing cables. This requirement from the customers and the limitations mean that the problem can not be resolved in this research. The last problem that directly relates to the action problem is the lower uptime of Jacketing Line 2. For the uptime of this machine, there are multiple underlying factors. During the production of cables, the cable drums need to be changed and this takes time. When the machine breaks down maintenance is necessary and the machine has a long changeover time between production processes. These factors are further explained in the next part where the core problem of this problem cluster is discussed.

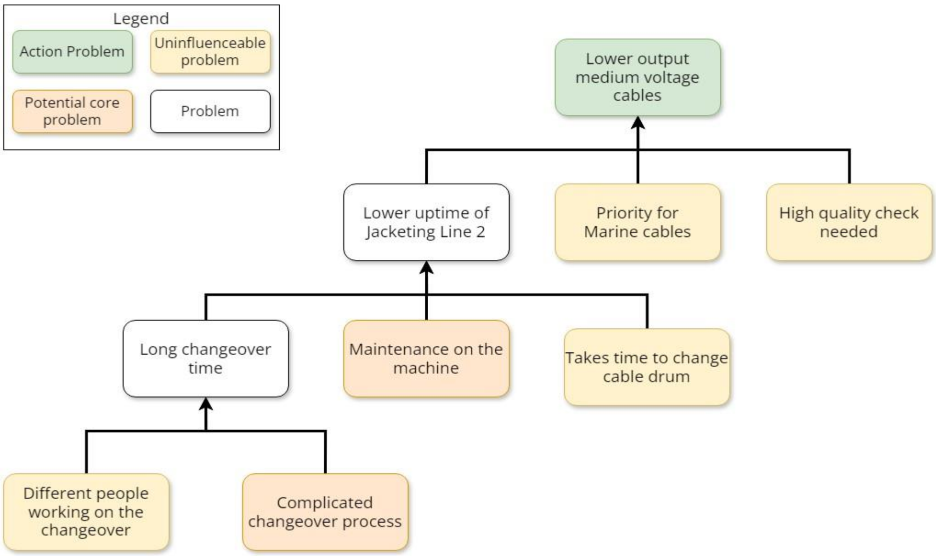


Figure 1: Problem cluster for producing medium voltage cables at TKF

1.2.3 Core Problem

In the process of the machine Jacketing line 2 there are multiple problems, one that can not be influenced is the time it takes to change the cable drum. The cable drums need to be exchanged when the capacity is reached during production. This is a standard process that is necessary for production to continue and has few steps on which changes can be made. The other problem is breakdown maintenance, during production, the machines in the production line can break down and have to be repaired. However, breakdown maintenance depends on what machine in the line needs reparations as well as the availability of the technical service. Factoring in these points the breakdownmaintenance is not a suitable problem to investigate to find an improvement for the bigger picture.

Next to these problems, there is still one problem left, the long changeover time when switching between the production of the different cable types. This changeover problem consists of multiple factors as well, the duration of the changeover process differs per shift as different employees perform the changeover and not every operator has the same experience with the process. Considering the workers work in shifts and do not perform only this process a variation between workers is normal and variance in the shifts will stay. The other factor that affects the changeover time and where improvements at TKF can be made is that the current changeover process is complicated and not optimized. This can be defined as:

"The changeover process of Jacketing line 2 at Twentsche Kabelfabriek is unoptimized and should take less than 6 hours instead of 8 hours."

This process itself has been developed by engineers at the company but it has not been verified if this process is performed optimally. Research is needed to see if there are changes that benefit the process and how these changes influence the process for the employees at the company. For this process there are multiple problem owners, the first problem owner is the company itself, the company is affected negatively by this unoptimized process as it influences the number of cables that can be produced. Other problem owners are the employees who make the schedule at the facility, they have to take the process duration into account and a lower duration would change the way they can schedule production. Next to these, there are the workers that need to perform the process, changes in how the process is performed need to take their preferences into account. In a solution all these problem owners need to benefit to solve the problem

1.3 Problem-Solving Approach

In this section, the research approach for tackling the problem at TKF is discussed. The main research question and the sub-questions are given. At the sub-questions, the steps that need to be taken to get to a conclusive answer will be presented. Next, the validity and reliability of the research will be explained by discussing the methods that will be used to acquire new data. To end this section the limitations of the research will be discussed.

1.3.1 Research Design

The research question that needs to tackle the core problem formulated in 1.2.3 and find a solution that can be used in reality is defined as:

"How can Twentsche Kabelfabriek reduce the changeover time of Jacketing Line 2 to address the congestion on the production line of medium voltage cables?"

To get an answer to this question the steps in the management problem solving method (MPSM), as formulated by (Heerkens et al., 2017), will be followed. In this method, the focus is on the application that follows from the theory and research. This is a good fit for this research as the goal is to find a solution that TKF can apply at their facility. In Figure 2 the MPSM is visualized, the process starts at the top and follows the processes clock-wise. When the last step of the MPSM is reached, the process begins again with the first step of the MPSM.

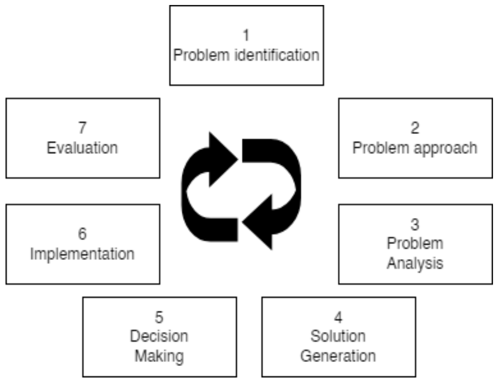


Figure 2: MPSM cycle (Heerkens, 2017)

For each of the steps in the MPSM separate sub-questions are drafted. Along with these questions, the steps that need to be taken to get to a conclusive answer are given. The first two steps, the problem identification and problem solving approach are tackled in this chapter while the other steps will be tackled in later chapters.

1.3.1.1 Problem Analysis

To get a good insight into the problem at hand a start is made with an analysis of the current situation. In doing this we can get a better understanding of what is the actual cause of the problem and see what a possible solution could look like. The sub-question that aligns with this is defined as:

"What are all the changeover process steps that need to be taken to start new production at Jacketing Line 2?

To be able to answer this question multiple investigation points are needed. These different points are used to verify each other and get a conclusive analysis. The process has been designed and documented by the company, this documentation needs to be investigated to find the what steps are noted down in the offical process flow. Another investigation point is the viewpoint of the employees who perform the process, these are important to get insights into the steps performed on the floor. While the last investigation point is witnessing the process as an outsider to verify the documentation and experience.

This problem analysis will start with assessing the official process flow that is documented by the company. For the situation at TKF, this can be done by checking the software of the company, Engage. In this software all the processes they perform are mapped and explained. The process steps are listed in order, as well as everything that needs to be done in each phase.

In the next step, different employees who work on the changeovers are interviewed, this way their experience and personal differences in the process can be used to get an accurate sighting and verify the process viewer. The focus of these interviews will be on the time distribution of the different steps in the process, an important piece of information that is is not available in the documentation of the company and necessary to check the process performance. The last step that is taken to research the process is to watch the process being performed live, this ensures that no crucial step is missed and verifies the previous research.

The results of all these steps will be combined into a Gantt chart that includes the time and employees needed for every step in the process. A Gantt chart is a way to visualize the distribution of all the steps in a process over time. On the left of the chart specific steps in the process are listed, and next the number of workers that are needed for every step is added. On the right of this list the time plan is added, for every step the time it takes and when it is performed is visualized. This could look like the Gantt chart found in this document on changeovers(Yfantisa et al., 2019) as shown in Figure 3:

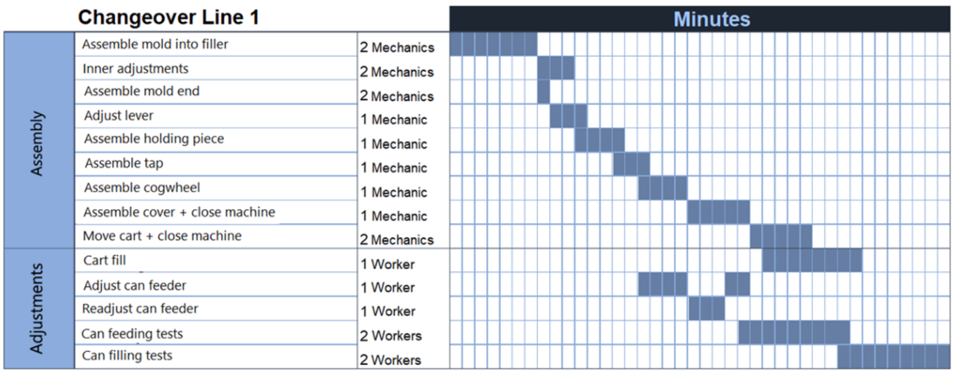


Figure 3: Gannt Chart of a changeover process

The previous steps to investigate the process are the most important to get an accurate answer to the question asked. But as with any company, management and the scheduling department are also important in a process and need to be regarded in the research. Decisions made by them include the number of operators on the line and when the process is performed in the day. To research this team leaders are interviewed on their experience with the process and what their approach is for the implementation of the process in the shift. Next to this, the planning department is interviewed on how processes are scheduled in the company and how the process is implemented in this schedule. Using all this information a list of preferences and requirements will be made that can be used alongside the Gantt chart as input data in improvement models.

1.3.1.2 Solution Generation

The goal for this step is to gain knowledge into what theories and models exist that are already researched and have a positive influence on the changeover process. The related sub-question is defined as:

"Which theories and models are mentioned in research that have shown to reduce changeover time in production?"

To be able to answer the knowledge question a literature review needs to be conducted to see what other researchers tested to improve a changeover process. For this literature review, it is important to take two factors into account, the models and the theories. Some models and theories may not be present at the same time in one article. To counter losing useful research articles in the search it will not be a condition to have both a theory and a model present in the results, but rather research both factors and learn how they work and what benefits they could bring.

Next to this, it is important to keep the focus on the duration of the changeover as the main part of the theory or model that is researched. Previous searches on the topic showed that the results only focused on changeovers will be hard to connect to the changes or calculations made on the changeover otherwise. This connection is very important to be able to draw conclusions on improvement results and implement them for TKF's changeover procedure. To follow up on this in the research it is also important to ensure that the research is not focused on the number of changeovers, as mentioned in Chapter 1.3 the production is determined on priority and that means that the number of changeovers also depends on this schedule and can not be implemented in this changeover improvement.

From this research the most common results in different articles will be collected and discussed, showing what the theory or model entails and why it applies to the process at TKF. This can then be used in the next step to make a decision on what to implement.

1.3.1.3 Decision Making

In this step of the MPSM, we take a look at how the researched theories and models fit into the situation at TKF. The related sub-question is defined as:

"Which theories and models are best fit to be able to reduce the changeover time of Jacketing Line 2 at TKF?"

For this step to be performed we will need to have theories and models from research that will be be gathered from the question in the previous step. Next to this, we will use the research done on in the problem analysis step of the current situation at the company to see what is a good fit for the situation at TKF. The information from these two MPSPM steps is combined so that the theory and model that fit the best can be selected. For this question it is important that next to just choosing the model a clearly defined deliberation on why the choice has been made for a certain model will be included.

After choosing the model that best fits all the criteria, the next step of the research is that it needs to be made and tested to see what the results are. The related sub-question is defined as:

"What is the performance of the chosen model on reducing the changeover time of Jacketing Line 2?"

By using the data on the current changeover process that was found in the problem analysis and theories that help in reducing changeover time a model will be made that can calculate possible processes that can lead to changeover time reductions. The results of those calculations can then be used to make a new process flow that can be implemented and help the company.

1.3.1.4 Implementation

In the second last step of the MPSM, the challenges that can arise when implementing a new process are researched. The related sub-question is defined as:

"How would the new process need to be implemented to ensure a good transition?"

Following the results of the research and the results that have come from testing the model, there is a good idea of what the new process needs to look like, but this is still theoretical. To get this theory into practice it is important to discuss with all interested parties what steps need to be taken to implement the new theory. As in the problem analysis, this will be discussed with the employees on the production line and the team leaders who are in charge of the operator partition of the shift. Next to this, the planning division will be involved in the discussion so they have the opportunity to give their view on how this process would affect the schedule.

After this has been gathered a final implementation guide will be made where the new process is explained clearly, along with the reasoning behind the changes. In this guide, the best way to implement the new process will be explained as well, with a roadmap of when a change would be best to make.

1.3.1.5 Evaluation

In the last step of the MPSM the implementation of the new process is evaluated. This evaluation is used to see what could be done differently in future research and make immediate adjustments to the process when problems are found. For this research, however, that specific evaluation may not fit in the available time. During the research, all the previous steps will be performed and a new process will be designed but implementing a process in the factory takes time, and even after implementation is finished it takes time to get valid results. This is mainly because the process is not performed at a standard time but depends on the product orders which means it may take weeks to be able to conclude what the improvements are.

If the process is not yet implemented at the company at the end of the research it can not be evaluated which means it is more difficult to give a total conclusion to the research. Despite this, an evaluation of the research can still be done by leaving out the implementation. In the evaluation all the previous steps of the MPSPM will be evaluated to see if any mistakes in the research were made that further research can learn from. Next to mistakes any findings in the research on methods that were helpful and can be recommended for further research will be given in the evaluation.

1.3.2 Validity and Reliability

For any research there is a high importance for validity and reliability, validity can be described as "An account is valid or true if it represents accurately those features of the phenomena that it is intended to describe, explain or theorise." as said by (Hammersley, 2018). Reliability is based on whether the research can be duplicated by another researcher to get a similar conclusion as can be seen in (Saunders et al., 2019).

For this research, the validity is of major importance in the first research part to investigate the current situation. In that part the interviews at the company will be held. The validity of the research is important at that point as employee preferences can influence the answers that the employees will give. An employee who needs to perform the process may want to steer the research to benefit the way they like to work. Some activities in the process can be easier for some operators and they might answer questions in interviews differently because of that. To make sure that this will not influence the validity of the research negatively multiple operators will be interviewed as this will balance out any preferences there are for the activities.

To further check the validity of the research it is important to also check in other ways what the process entails. This is done by checking the process in person to see what activities are performed and how they are implemented in the process. While also interviewing other employees that know the process to get an outsider's view next to the interviews with the operators that perform the changeover process. These employees are the process engineers that work on production processes at the company, the team leads who divide the operators over the activities and the scheduler that knows how much time the process takes in order to put it in the schedule.

As for the reliability of this research, the interviews are the main data gathering where keeping the reliability high is difficult. Interviews with the employees are performed once and can not be repeated by other researchers which gives big importance to the execution of the interview. This starts with making sure that there is no bias in the interview questions, which could influence the interviewee may be influenced and lead to answers that fit what the researcher already thinks(Saunders et al., 2019). Next to this, there is also the importance of the phrasing of a question that influences this, a closed question will not gather a lot of new information while an open question may not get the answer that is useful for the research. As mentioned by (Long & Johnson, 2000) to ensure high reliability it is also important to keep the interview consistent for all the participants. This way it is ensured that all the answers are corresponding and can be combined. Next to this, it is important to repeat topics in multiple questions to be able to ensure the quality of the answers.

To ensure the validity and reliability of the research the most important method is to document every step correctly, this includes reasoning for why any information is important for the research and why the argument can be made from that information. This way any personal reasoning from the researcher does not have a negative influence on the result of the research.

1.3.3 Limitations

In this research, there is a high dependence on the interviews that are done with the employees. These need to result in a good overview of the changeover process, but this is also where a limitation of the research comes into play. Processes are ever-changing and not always performed in the same way, the process can change depending on problems that arise when working like machine breakdowns or any activities in previous shifts. Another factor that may limit the quality of the data gathered in the interviews is that fresh experiences, how the process went in the last weeks, may affect the view of the individual on the process and alter the view of the process. To counter this the interviews need to be compared so that any outliers can be disregarded.

1.3.4 Deliverables

The deliverables of this research are constructed based on the needs of the company, the requirements of the university and the time that is available for the research. The deliverables are defined following the structure of the research.

Gantt chart

To get insight into the current situation at the company the changeover process is visualized using a Gantt chart, this chart is used to see at what time in the process specific steps are performed. In addition to the Gantt chart, the requirements of the company and other findings are listed.

Optimization model

To be able to improve the situation visualized in the Gantt chart, the requirements and findings from research into theories are used to make a mathematical model that can calculate where improvements can be made in the process to reduce the changeover time.

Recommendations

Using all the data gathered from the theories, the results from the mathematical model and discussions with employees at the company a recommendation will be given on what to do to improve the process. This recommendation will include the reasoning behind changes and how they are best implemented at the company.

Thesis

At last, the research in which the entire process is discussed is made. Here all the reasoning for choices made in the research and in making the other deliverables is given, and depending on the status of the implementation the results that the optimization has achieved. To conclude the thesis an evaluation of the entire process is given where learning points are discussed.

1.4 Theoretical Framework

The focus of this research is on process optimization, there are multiple concepts in this field of study. Some of the general concepts and what they consist of are explained in this chapter. Next to the general concepts some main concepts are discussed that are closely related to the research.

1.4.1 General Concepts

In this day and age scarcity of resources has made it so that companies seek out every way they can to get an advantage over their competitors(Venkrbec et al., 2018). This means that every step of the production is investigated so that it can be optimized. To get this optimization the companies rely on computational models that can tell them based on their data where the problems are in the company. Generally these models are expressed like this(Venkrbec et al., 2018):

Minimize f(x), subject to h(x) = 0 and g(x) ≤ 0, as you want to minimize the decision variables (x) while keeping the constraints into account.

To solve these functions there are two usual methods, heuristics and mathematical programming. Heuristics are faster and can handle non-differentiable functions but have the downside of not giving an "optimal" solution. This is why they are mostly used in cases where it would not be possible to solve the problem efficiently by using exact algorithms. The mathematical programming method's major benefit is that it can give an exact optimum, one of the methods that covers this is linear programming (LP) where the optimization problems are solved using linear objective functions and constraints with continuous variables. A similar method is mixed integer linear programming (MILP), in this method, the variables can be discrete which allows bounding specific variables to a maximum or a minimum depending on the cases at the company (Venkrbec et al., 2018).

Along with models that can solve the optimization problems of the company, enterprise resource planning (ERP) systems have taken a major role in companies. An ERP system can help the company manage all their systems and their resources by combining them all in one software. This evolution has given companies a better understanding of their processes and where the problems are. They can standardize and improve their processes which helps increase efficiencies and consistency across the company (Davenport et al., 2004).

1.4.2 Changeover

For this research, the optimization is focused on changeovers. To optimize a changeover correctly it is important to correctly define what a changeover entails. At a production facility, multiple machines are used on a production line to be able to produce the products. At times a company may want to produce different products that are similar to each other. To do this machines are adapted so that the new production can happen. The adaptation of a machine is called a changeover. This changeover happens when the batch of the previous production is finished and consists of three stages (Mileham, 1999):

- The run-down: This is the last phase of the previous production, in this stage, there may be possibilities to prepare for the next production if the employee has the time.
- The set-up: In this step, the previous tooling and equipment are replaced with the tools needed for the next production.
- The run-up: In this stage, the new production has already started, and adjustments and checks can be made so that the desired production level can be achieved.

A changeover can also be separated by the activities as discussed in (Ferradás, 2013), the activities of a changeover can be internal and external. Internal activities can only be performed when the machine is shut down which means there is no output of products, while external activities can be performed when the machine is running. The differentiation is important for changeover time reduction, as being able to change activities from internal to external saves reduces the total time of the process.

Chapter 2
Current Situation

This chapter provides an analysis of the current cable production processes at TKF. Initially, it discusses the cable production scheduling, taking into account all relevant factors. Following this, it focuses on the production routes for medium voltage (MV) and subsea cables. Building on this, more detail is given for the scheduling processes and the distribution of work during the shifts. Finally, it discusses an in-depth description of the JA2 changeover process, including the duration of each step and the critical decisions that need to be made.

2.1 General Production Process

This section focuses on the process of producing cables at TKF. The scheduling of cable production is initially outlined, with a focus on the market and factors that are important in a day. Following that, the production sequence for both types of cables is described and shown.

2.1.1 Scheduling

For the production of subsea cables, the scheduler starts with the overarching order from the customer. This order specifies a six-month period during which the customer requires a specific cable to be produced. After receiving this schedule, the scheduler translates it into a detailed schedule spanning approximately three weeks for the production of the cables within the facility. Using this global schedule, the scheduler schedules the day-to-day production for the entire facility for the upcoming week. In this schedule every machine has its own timeline, these timelines show the separate production processes performed on each machine. The combined timelines give an overview of the production in the entire facility during the week.

The production schedule for Jacketing Line 2 prioritizes producing subsea cables, as these cables are of the highest importance. When there is no subsea cable to produce, the machine is allocated to produce medium-voltage cables. These medium-voltage cables can also be produced at an alternative production location. The production tasks are divided between the locations, allowing for flexibility in production. This flexibility benefits the production at Lochem, as the alternative location can take over part of the production load when there is an increased need for subsea cable production.

The daily schedule is intended for the team leads of the different shifts. This schedule details all the various production tasks that need to be performed and what process is prioritized that day. The team leads utilize this schedule to determine the number of operators required for each shift to ensure the completion of all production tasks. Depending on the number of employees present the team leads can decide to forego some production tasks to be able to perform prioritized production tasks.

2.1.2 Routes

The processes that are scheduled need to be produced at the facility in Lochem. To be able to do this efficiently the products follow a specific route in the facility. For both the production of the medium voltage cables and the subsea cables, Jacketing line 2 is used which is where the problem with the changeover comes into play. To understand the total production at the facility better both routes will be explained here.

2.1.2.1 Medium Voltage

To be able to start producing medium voltage cables at the location in Lochem cable cores that are produced in the production facility in Haaksbergen first have to arrive. The process at the Lochem facility begins with isolating the cables with multiple layers, which leads to the development of gasses. The cables are degassed before continuing production of the cables, after which they can be stored depending on the schedule of production. In the next step of the process, the protecting layers are added.

As medium voltage cables have two different types of cores, the production of cables is further divided. For the first type, the cable with a smaller diameter is screen-stranded after which three cables are twisted together to form a single cable. After the cable is twisted further layers of screenstranding are added. The second type consists of a single, large-diameter core that immediately receives multiple screen stranding layers.

Since medium voltage cable production is not continuous the cables are stored on cable drums. The next step in the production process is to jacket the cables, this is done on Jacketing line 2 when no other production is necessary on the production line. Next, the cables are checked to make sure they meet quality standards. After passing quality control, the cables are kept at the facility before being transported to the client.

In Figure 4 the production scheme of the cables is visualized in a flowchart. This gives a good overview of the entire process, which shows how the different routes for specific cable types are separated and how Jacketing Line 2 is implemented in the route.

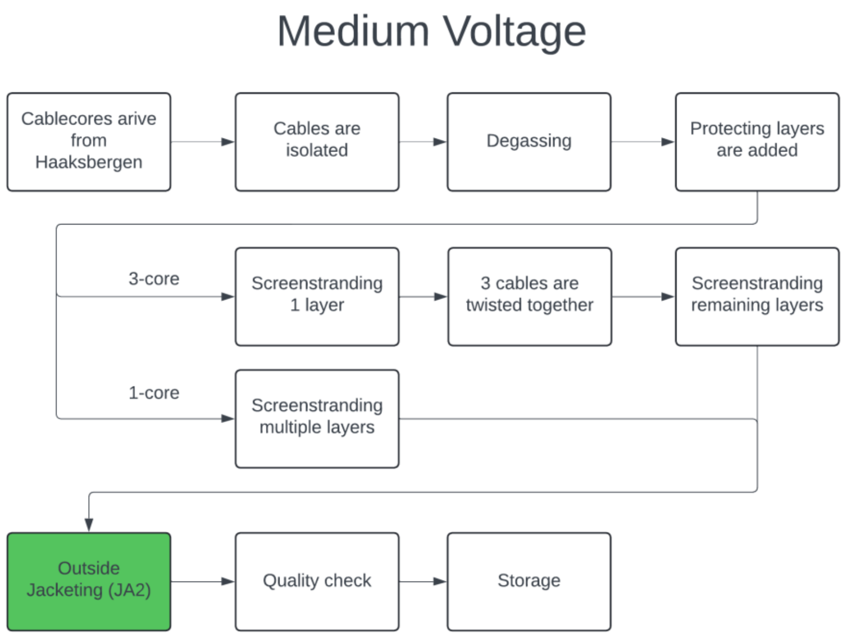


Figure 4: Flowchart of the production of medium voltage cables

2.1.2.2 Subsea

For the production of subsea cables, the first steps of production are the same as for medium voltage cables. First, the cores arrive from Haaksbergen, after which they are isolated and degassed. For the production of subsea cables, extra steps are necessary, the cables get a layer of tube stranding added after which there is a weld & jacketing process. In this process, a protection layer is welded and a jacketing layer is added on the same machine. When this process is finished 3 of these cables are twisted together to turn into one big cable.

In the step after twisting the cables together, a filling is added to the twisted cable on Jacketing Line 2 to fill in the gaps and help with isolation. In the next step, armouring is performed before passing through Jacketing Line 2 again to add the outside jacketing layer. Next up is checking the cable to ensure it meets the quality standards, after which the cable is stored in the barge. When this barge is filled with multiple subsea cables the barge is pushed to the storage at a separate location before transportation to the customers.

To get a good overview Figure 5 shows the processes that each Subsea cables go through as explained previously. Each step that is visualized dictates a part of the process where a change is made or the cable is moved.

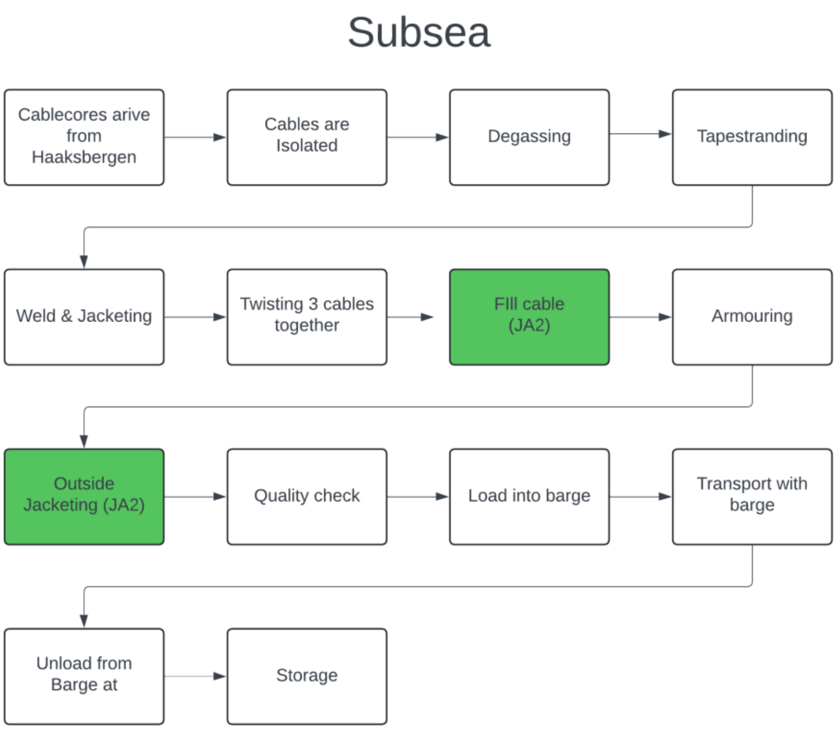


Figure 5: Flowchart of the production of subsea cables

2.2 Changeover Process

To be able to find the current changeover process at the company interviews with personnel were done. Operators who perform the process were interviewed to see the exact process that currently takes place while managers and scheduling personnel were interviewed to find out what the processes for the production of cables throughout the facility look like.

The facility uses several machines to produce different types of cables, but because Jacketing Line 2's cable production processes overlap, this machine needs to be prepared for multiple productions. This occurs during the transition between production processes, the production overview indicates that the machine can perform three different types of production. The machine can create the outer jacket for medium voltage cables as well as the filling and outer jacket for subsea cables. There exist six possible changeover processes that can be scheduled in succession and each of these processes has a set of steps that must be completed, each with a different time requirement.

A Gantt chart is created for each process that shows how long it will take to complete. Process engineers formulated these procedures, but it is important to collect personal information to make sure the execution matches the plan. Discussing the procedure with the workers who carry it out contributes to gathering the data. The charts can be filled in with their knowledge to show the current state of the process.

In Figure 6 the Gantt chart for the changeover process from filling to jacketing of subsea cables is shown. The number of people that are stated shows the minimum number that is necessary to perform that specific process, not the number of people working on the entire changeover. The timeline is divided into periods of 30 minutes where it is possible to perform multiple processes at the same time depending on the process that needs to be performed.

Time line JA2 Fill to Subsea

Process				When the process is perfomed during rebuild													
Where	Type	Process	Number of people	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Line	Cleaning	Rinse with PVC	1	x													
		Remove and clean head	1		x	x											
		Place 'heson'bucket	1			x											
		Pull and clean 'worm'	1				x										
		Drain hopper and put material away	1				x	x									
	Set up	Put 'worm' back	1				x	x									
		Place and attach head	1						x								
		Turn on the heating of extruder	1							x	x	x					
		Place the correct spray attachment	1										x				
		Fill hopper	1											x			
		Center head	1											x			
		Retrieve winch	1											x			
		Grounding forerunner	1												x		
		Rince extruder	1												x		
		Set up waterbucket	1												x		
		Set up height cablelift	1												x		
		Set up Lint printer	1												x		
		Inkjet printer to storage	1												x		
		Position cable	1												x		
		Place startingpoint	1												x		
		Put cable through lift and tune lift	1												x		
		Place vacuum	1													x	
		Put cable trough head	1													x	
		Place 'vlieter'	1													x	
		Tension winchcable	1													x	
		Control cablelift	1													x	

Extra processes	Name														
Time between	Break		x												

Figure 6: Gantt chart changeover filling subsea cables to jacketing subsea cables

The changeover of Jacketing Line 2 consists of two main subprocesses, cleaning the line and setting it up for the next process. The cleaning process starts with rinsing the head and extruder which removes excess material from the previous production. After this, the worm is removed from the line and cleaned, next up the hopper is drained.

After the cleaning is done the machine is rebuilt to fit the new production process, this starts with adding the worm back in the line, after which the extruder head for the new process is added. During the changeover process, the extruder head needs to be heated before continuing. After this process, some smaller processes can be performed in little time for which in total about an hour is scheduled. During the changeover the operator takes a break of 30 minutes, this is done between processes and depends on the schedule of the day.

In Figure 7 the Gantt chart for the changeover from jacketing subsea cables to jacketing the medium voltage can be seen. There are two main differences for this changeover process compared to the previous process. The first one is the possibility that the subsea cable from the previous production is not yet taken away which delays the changeover. For the production of subsea cables, there are highways attached to the line that the big cables pass through, these are not needed for the medium voltage cables as they are stored on cable drums. This leads to the second difference in the changeover process as these highways have to be detached before producing medium voltage. Next to these differences, some other small processes are performed during this changeover.

Time line JA2 Subsea to Medium Voltage

Process				When the process is perfomed during rebuild															
Where	Type	Process	Number of people	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Line	Previous process	Putting away cable from previous production	2	x	x	x	x												
	Startingpoint	Remove Highway from line and put it away	2					x											
	Endpoint	Remove Highway from line and put it away	2						x										
	Cleaning	Drain hopper and put material away	1							x									
		Rinse with PVC	1							x									
		Remove and clean Qu200 head	1								x	x							
		Pull and clean 'worm'	1										x						
	Set up	Put 'worm' back	1										x						
		Place and attach Qu100 head	1											x					
		Place the correct spray attachment	1												x				
		Put right material at line	1													x			
		Turn on the heating of extruder	1													x	x	x	
		Set up inkjet printer	1															x	

Extra processes	Name		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Time between	Break		x															

Figure 7: Gantt chart changeover jacketing subsea cables to jacketing medium voltage cables

Four additional potential changeovers exist in addition to these two that might need to be performed. Between all the processes the primary differences are switching between Medium Voltage and Subsea cables compared to switching between the Subsea production type. For switching between production of the same cable type the highways operation are not necessary which makes these processes different from the other changeovers. Appendix A contains the Gantt charts for the other four processes.

From discussions with the operators and team leads there are some processes that stand out, the most apparent one is the heating of the extruder. Unlike the other activities this process can only be performed when almost all of the other processes are finished. Next to this it takes 1.5 hours to complete, during which only setup checks can be performed. Another activity of interest to investigate is the highway operation, these highways need to be attached and detached from both sides of the production line. This activity stands out since it needs to be performed with 2 operators, which is a big portion of the available operators due to only having 4 operators available. This activity takes an hour but a benefit for this process is that it can be scheduled at any time during the changeover as no process depends on it to be started.

2.3 Summary

In this chapter we discussed the current situation at the facility in Lochem focusing on the entire production process and investigating the changeover process of Jacketing Line 2. First we discussed scheduling of production after which we investigated the current situation of the changeover process of Jacketing Line 2. The company's production schedule begins with orders for subsea cables, which are prioritized in the schedule. If there is space in the facility that space is used to produce the medium voltage cables. Only on Jacketing Line 2 all the cable types are produced as the other production processes can be performed on separate machines.

There are 3 production types that need to be produced on Jacketing Line 2, jacketing subsea, filling subsea and jacketing medium voltage. Because of this there are 6 different changeover processes, these processes are very similar but there are differences. For the changeover between medium voltage to jacketing subsea or filling subsea highways are added to the production line an when switching from jacketing or filling subsea to medium voltage cables, the reverse is the case. In all processes the extrusion head needs to be switched and cleaned, the hopper is refilled with the correct material, the extrusion head is heated, and small setup settings need to be changed.

Chapter 3
Changeover Literature Review

This chapter explains the process and findings of research into theories and models that can be used to improve the changeover processes at the company research. For the literature review, previous research is gathered on proven theories and models. The main research point that we focus on is the changeover time, this is the problem at the company we want to address and to be able to make improvements more data is necessary.

First, previous research on theories that apply to changeovers are discussed keeping into account how the theory fits the current situation at the company. This is done in the following sections where theories and models are explained that were checked during the literature review into the topics.

3.1 Single Minute Exchange of Die

Researching theories on the optimization of changeovers leads to multiple articles on theories that can help with improving the process of a changeover. A common result when researching is the Single Minute Exchange of Die (SMED), this is a theory that was developed to enable shortening changeover times of machines in production processes as described in (Niekurzak et al., 2023). The goal of the method is to simplify the whole process of changeovers so that they are performed with as few tools as possible. The theory was developed in the 1950s and 1960s by a Japanese engineer by the name of Shigeo Shingo.

In the development of this method, the activities of changeovers are divided, this division is determined by checking if the activity is internal or external. The activities mentioned are based on retooling, which is the process where a machine is prepared for the production of a new process. During this process, the tools that differ between production processes are changed and other activities for the production are prepared (Niekurzak et al., 2023). A changeover process can only be performed when the production is stopped and the process itself has no added value for the company.

Following the research done by (Niekurzak et al., 2023), the SMED method and how it can help to reduce the changeover time can be divided into four stages:

- Making sure that tools and machines are placed in the right place and work correctly
- Separating of internal and external reinforcement
- Transforming internal and external activities
- Improvement of all aspects of the changeover, where the production line layout is analyzed as well as all activities are measured in time

To implement the SMED method it is best to start with monitoring the current process so that all the movement of employees during the activities is monitored. After which the process is analyzed with everyone involved to discuss the activities. This way the internal and external activities can be located and transformed to decrease the changeover time.

3.2 Models

Next to the research on theories for improving production processes, there are also other methods to investigate potential improvements. During the 20th century, there were the first starts with linear programming to help with optimization as G.B. Dantzig published a paper that involved linear programming in 1947 but records show that earlier developments involved optimization by linear and nonlinear programming as well (Du et al., 2009).

The research on optimization developed further in the second part of the decennium, where other divisions in optimization like integer programming and stochastic programming were researched. Alongside the development of different types of optimization models computing speed increased, this increased the number of calculations that could be performed and increased the possible complexity of the models (Bixby, 2012). These developments in the 20th century into the current age led to models that are used to improve production processes at companies in the current age.

3.2.1 Scheduling problem

For a production company to produce products with an efficient process flow they can make use of scheduling problems, in these models a schedule can be changed per iteration to calculate if the makespan of the product decreases (Das et al., 2009). These calculations are done by implementing different programming methods as shown in (Das et al., 2009).

A typical scheduling problem is the job shop scheduling problem (JSSP, (Xiong et al., 2022) found that " a classical JSSP can be described as follows: in a job shop environment containing several machines $\mathrm{M} = \{\mathrm{M}_1, \mathrm{M}_2, \cdots, \mathrm{M}_m\}$ are a number of jobs $J = \{J_1, J_2, \cdots, J_i, \cdots, J_n\}$, each job, say J_i, contains a serial of operations $O_i = \{O_{i1}, O_{i2}, \cdots, O_{ij}, \cdots, O_{ini}\}$ which need to be processed in a predefined technological sequence. Each operation is assigned a machine in M to be processed with a given processing time p_{ij}. Sequencing need to be done for operations in all machines to minimize the maximum completing time of all jobs, i.e., to minimize the makespan."

A scheduling model like this is most often used in a situation where multiple machines are needed for the production of a product from start to finish. However, for a changeover process like at TKF it could be used, jobs are the activities performed during the changeover and machines are the operators that perform the activities. This brings some added problems however, some activities need to be executed by multiple operators together which is not something that happens in a classical JSSP. To get a more accurate model for the situation at TKF other models need to be explored.

3.2.2 Mixed Integer Linear Programming (MILP)

In (Das et al., 2009) multiple examples are given of linear programming that can be used to address production planning methods, alongside different models that can be used to calculate sequencing problems. These programming models calculate the completion time of a production process based on the availability of the necessary tools for the machine. As can be seen in ((Kentli et al., 2013)and (M. Pinto et al., 2007) as well, there is a connection between optimizing changeover times and linear programming. It has been shown that there is the possibility of calculating the minimum time of sequences, this can also be applied to changeovers by using Mixed Integer Linear Programming (MILP).

Mixed integer linear programming uses an objective function, for the current situation, this would be an objective function to minimize the changeover time. To be able to make the calculations variables and constraints are necessary. For the changeover calculation, the priorities between process steps need to be known as well as the duration of each separate process step. Using the constraints the objective function can be solved to get to an optimal solution. But just like the JSSP a MILP is not fully applicable to the changeover process at TKF due to parts of the situation not being used for the calculation.

3.2.3 Hybrid scheduling problem

The typical scheduling problem as described previously can be used to improve business processes, but some models are focused on resource allocation optimization in processes. These are hybrid scheduling problems where iterative problem-solving is done while also keeping the resources into account. This is achieved by combining priority rules with a mixed-integer linear programming model(Osman, 2021). A model like this can keep worker availability into account as well as look at successors and predecessors to give weights to activities and optimize a schedule using an algorithm.

One of the models that fits accurately to the changeover situation and has been researched extensively is the Resource Constrained Project Scheduling Problem (RCPSP). For a clear basis on what the model entails the research by Hartmann and Kolisch (2000) is used. An RCPSP problem consists of n+1 activities for which each activity needs to be processed to complete the project. Of these activities the problem needs to have a start and end, these are denoted by activity 0 and n+1. The other activities of the process interrelate for multiple constraints.

The first constraint for an activity is the precedence of the activity, a new activity can only begin if all prior processes have been finished. For example, in the process of building a cabinet, there are multiple activities. One of these is that the planks have to be put together, to be able to do this other activities like putting screws in the correct place need to be finished as the activity can not start otherwise.

The other constraint that influences the activities is the availability of the resources. In a production process, multiple activities might need to be performed by the same machine, a schedule would need to be adapted to make sure that the activities are not scheduled simultaneously.

The result that an RCPSP is looking for is a minimization of the completion time for all activities while keeping precedence and resource availability in mind. This is why the model fits the situation at TKF, for the changeover some activities can only be performed after other activities. Next to the precedence, there are the resources in the case of TKF the availability of operators, each activity needs to be performed by the operators at the production line and there is a limited number of them during the changeover process. Using RCPSP we can find an optimized schedule for the changeover process while also involving the number of available operators to work on the process.

In the field of research on RCPSP models, there are a lot of variations that can be used as implementation for processes. These variations can be extensions based on other objectives, different constraints, activity characteristics and also on how the problem is solved (Ding et al., 2023). For our RCPSP model, we want to focus on time usage, but there are also other objectives where the focus can be on the cost of the process, the quality that the process will result in or on resource usage.

In the situation at TKF, we need to look at the precedence between activities and availability of people for the constraints but there can also be other considerations. Some activities may not be mandatory or an activity may have a deadline for when it has to be completed during the process. For resource constraints, there are also model usages where the resource is expandable like raw materials or budgets.

There are model variations in which the activities can be paused when working on them and continued later to perform other activities, but also multi-skill where human resources or multi-purpose machines are used. A model needs to be able to use this information on the skills of these resources when scheduling to make sure that no unnecessary waiting is done.

Next to these variables, there are 3 solutions used for the RCPSP: the exact algorithm, the heuristic algorithm and the meta-heuristic algorithm (Ding et al., 2023). For the exact algorithm an exact solution is calculated which is best but for this method, the solution time increases exponentially when adding complexity. The heuristic algorithm uses heuristic rules to find the best solution within a range this is most often done with the serial generation scheme or the parallel schedule scheme, where the serial method arranges in order of priority and the parallel method wants to determine the feasibility of activities in the time interval. Lastly, there is the meta-heuristic, an improvement on the heuristic algorithm, this method uses a starting point from a heuristic algorithm on which it improves by using optimization techniques. For example, by using local search where solutions closely related to the one found are compared.

For this research the main choice was based on what solution method to use, the current situation with constraints is known and for this situation, a normal RCPSP model is adequate as it fills all of the boxes. Since we have multiple variables and small changes could come up during research we would quickly run into problems when using an exact algorithm. This is why we decided to use a heuristic algorithm with a solver that uses multiple priority rules to find the optimal schedule in the range. Using multiple priority rules when calculating a schedule results in a lot of the possible solutions already. Running any extra optimization would take extra time and there is not any extra data that a model can use to optimize the schedule. Since the changeover process at TKF only needs to take precedence and resource usage into account.

3.3 Summary

In this chapter, we discussed the theories and models that can be used in the improvement process of the changeover at TKF. We first discussed a theory that is frequently applied to changeover processes, SMED, this method looks at the activities in the process to find if there are changes that can be made when they are performed. Mainly investigating if activities can be performed when the machine is still running as well as analyzing the duration of each activity.

Next to the improvement theories we also discussed the possible improvement models. At first we discussed some history on these models, the models were mostly developed during the 20th century and got complexer leading to more possibilities to use them for the current production processes. After this we disussed the job shop scheduling problem, where jobs are scheduled on machines and optimized by using sequencing.

After this we discussed the MILP, this is a programming method where we want to minimize an objective function based on the constraints. This is very similar to the next method that uses similar methods but is more specific to the changeover process. The RCPSP, this model calculates a schedule based on the necessary resources. For the case at TKF the model can use the number of operators available and the precedence between activities to calculate a schedule that takes the least amount of time.

Chapter 4
Resource-Constrained Project Scheduling Problem

Improving the changeover process at TKF is done by combining improvements SMED can result in with a scheduling model that generates an efficient schedule. In this chapter, the implementation of these two improvement strategies will be discussed. First, we start with investigating if implementing SMED at TKF can be done, this is done by discussing activities of the changeover with operators to see what changes can be made to the activities and the schedule. After this the scheduling model, Resource Constrained Scheduling Problem (RCSP), is explained in more detail and how it is used to calculate a schedule for the changeover process at TKF.

4.1 Single Minute Exchange of Die (SMED)

The focus when implementing SMED is on the entire process, the goal is to find processes that are performed during the setup process that can be performed during production, trying to transform internal activities into external activities. When investigating the changeover process at TKF, as discussed in Chapter 2.2, there are no activities that meet this criteria.

The process at TKF currently is designed in a way that the setup during the changeover only consists of activities that can not be performed during the production. This means that there are no activities that can be changed from internal to external. Despite SMED not applying to the changeover at TKF in the standard method we can still make use of the ideas mentioned in the theory. The theory focuses on analyzing the activities and performing them at a different time in the schedule. Using this we find that in the current schedule of the changeovers, there are activities of interest for improvement projects, discussing these can help to make sure that they are implemented correctly in an improvement model.

The first process that falls under these activities is the activity of heating the extruder, at the moment the process is scheduled at the latter stages of the changeover process. Discussions with operators and process engineers lead to some new findings on when this activity can be performed. In the facility in Lochem, there is the possibility to start the heating process of the extruder separately from the production line. Performing this activity in this way could lead to other activities that are now performed before or after the heating to be scheduled separately.

Other activities that fit in the improvement processes at TKF were found when discussing the process with operators at the line, the operations on the 'worm' as during discussions with operators it was made clear that improvements can be made to the operation order with the work distribution not clearly defined.

Next to the aforementioned activities, to be able to model the problem accurately other activities are identified to take into account. Important activities are the operations on the highways when the process switches between the production of medium voltage and subsea and the other way around. This is only not the case when switching between the different operations on the subsea cable as these both need the highways. The work on the highways requires two operators and at the moment other activities are not performed simultaneously, a model needs to look into the possibility of performing other activities with extra operators. For the model, another important activity is the operation on the head as discussions with operators found that time can be gained there, mainly making sure that if possible this is done right after each other.

4.2 Resource-Constrained Project Scheduling Problem (RCPSP)

In this section first, the mathematical formulation behind the RCPSP is explained, after which the implementation for the situation at TKF is discussed along with this implementation the choices made to be able to get accurate insights for the company.

4.2.1 Mathematical formula

The famous mathematical formulation of the RCPSP that started the research into the topic is the one produced by Pritsker et al. (1969). This is a binary formulation, where the variable is equal to 1 if activity i starts on time t. Using this formulation the process activities combined with the possible starting times are equal to the number of variables, with two extra as the start and end are separate. (ARMAS, 2024b)

$$
\begin{aligned}
&\text{Minimize} && \sum_{t \in T} t x_{n+1,t} && && (1)\\
&\text{s.t.} && \sum_{t \in H} x_{it} = 1 && \forall i \in N && (2)\\
& && \sum_{t \in T} x_{jt} - \sum_{t \in T} x_{it} \geq p_i && \forall (i,j) \in E && (3)\\
& && \sum_{i \in N} \sum_{\tau = t - p_i + 1} r_{ik} x_{i\tau} \leq R_k && \forall t \in T, \forall k \in R && (4)\\
& && x_{it} \in \{0,1\} && \forall i \in N, \forall t \in T && (5)
\end{aligned}
$$

Figure 8: Mathematical formulation RCPSP Pritsker et al. (1969)

The first equation of this formulation denotes the objective function, it represents the minimization of the total time the process takes. After this, the other equations denote the constraints of the objective function. The first constraint (2) is there to make sure that activities are only connected to one start time. The second constraint (3) denotes the precedence constraints E between the activities of the process, a new activity j needs activity i to be completed before it can be started. To do this the second constraint (3) checks if subtracting the start time of activity i from the start time of activity j results in a quantity bigger or equal to the duration of activity i. For the final constraint (4) the formulation checks for resource availability, the sum of the resources that are used for the activities in time t can not exceed the total available resources. (ARMAS, 2024a)

This mathematical formulation can be used to find optimizations for TKF, the model is implemented in Python 3 and makes use of Gurobi, a general-purpose solver. The code is shown in Appendix B.1. This code is the one used in ARMAS (2024b), this fits accurately to the situation at hand as the inputs are activity-based. Small adaptions to the code were made to make it easier to execute the model for the different processes and the changing availabilities.

4.2.2 Model Input

For the RCPSP to give optimized schedules for TKF data needs to be put into the model. For the scheduling model, we take the activities from the Gantt chart to find the duration and the precedence between activities.

In Table 1 an example activity table that is used for the scheduling model is shown, this is the activity table for the changeover process from jacketing Subsea cables to the filling of Subsea cables. The activities used in the activity table are further detailed in the activity list in Appendix C.

This table depicts the activity, the index, the duration of the activity and the precedence between activities. Next to these factors, the table shows the resources the activities require to be performed, in this case, the availability of operators. For the availability of operators, the table shows what operators are necessary for the process to be performed, this is done with binary values, a 1 indicates that an operator is available while a 0 means they are not. These are defined by checking with the previous activity to ensure no workers can be scheduled in activities where they would elongate the process.

For the situation at TKF, six setup processes have small differences between the activities, which is why we use online repositories in Github, to be able to import the different tables for the model in Python. These repositories can be requested by the code and simplify implementing the schedule data, the data for each activity can be seen in Appendix B.2.

activity	**idx**	**description**	**duration**	**precedence**	**resources**	**Worker 1**	**Worker 2**	**Worker 3**	**Worker 4**
A	1	Putting away cable	120	Start	[1,1,0,0]	1	1	0	0
B	2	Rinse	30	A	[1,0,0,0]	1	0	0	0
C	3	Remove/clean head	60	B	[0,1,0,0]	0	1	0	0
D	4	Work on worm	30	B	[1,0,0,0]	1	0	0	0
E	5	Drain hopper	60	C	[0,1,0,0]	0	1	0	0
F	6	Place and attach the head	30	E	[1,0,0,0]	1	0	0	0
G	7	Turn on the heating of the extruder	90	F	[0,0,1,0]	0	0	1	0
H	8	Hopper, head, forerunner	30	E	[1,0,0,1]	1	0	0	1
I	9	Extra setup	30	E	[0,1,0,0]	0	1	0	0
J	10	Cable preparation	30	I, G	[1,0,0,0]	1	0	0	0

Table 1: Activity table of changeover process Jacketing Subsea Cables to Filling Subsea cables

4.2.3 Number of Operators

The mathematical formula can calculate optimal schedules based on the input from the data and the constraints that this input gives the model. These give the possibility to find optimized schedules for the process, the output of the model we use is based on the production line with an availability of 4 operators to perform the changeover. The availability of operators was derived from discussions with the team leaders and operators, it was concluded that a team lead can at max schedule in 4 operators. Depending on what production process at the facility has the highest priority other processes can be stopped to be able to schedule 4 operators.

For the company and a new schedule, it is beneficial to investigate the impact of lower operator availability due to absence leave or sickness. We do this by running the model with the availability of 3 operators for the 6 changeover processes to give an accurate overview of the impact this change would have on the entire process and discuss the significance for TKF. For multiple activities in the changeover process, more than 1 operator is necessary, because of this the model is not run for fewer than 3 operators. The result of running it for two operators would be worse than for 3 operators as activities that need 2 operators can not be performed at the same time as any of the other activities.

4.3 Summary

In this chapter, we discuss the implementation of the theories and methods discussed in Chapter 3. We start with the SMED theory, this theory was found to not apply to the changeover process at TKF. The current process has no activities that can be performed while producing so no activities can be transferred from internal to external. After finding this we shifted the focus to analyzing the activities in the process to see for each activity what stands out and needs to be known before implementing a model.

After discussing the theory and the activities we discussed the implementation of the RCPSP model for the changeover process at TKF. At first, the mathematical formula is discussed, this formula is an objective function in which a minimization of the total time of the process is done based on precedence constraints and activity duration. This model was implemented using Python code and a general-purpose solver to find the best solution. Next, the input for the model was discussed, the model uses an activity table in which the duration of an activity is denoted, the precedence between activities is shown as well as the resource usage of each activity is used.

At last, we discussed the number of operators for which the model was run. The model was run for 3 and 4 operators, from discussions with team leads it was noted that 4 operators is the maximum the team lead can assign to the process without other crucial processes shutting down. Next to this, it was tested with 3 operators to see how performing with fewer operators would affect the outcome. Fewer than 3 operators would not be beneficial when scheduling as this way no processes can be performed simultaneously if processes need multiple operators.

Chapter 5
Results and Validation

In this chapter, we discuss the results of applying the RCPSP model discussed in Chapter 4 to the changeover process at TKF. The model aims to provide a new schedule for the different changeover processes. At first, we will compare the schedules from the model with 4 operators available to the current situation and see where the differences occur. After which we will discuss the comparison of running the model with 3 operators with the schedule from using 4 operators.

5.1 Results 4 Operators

Running the code of the RCPSP formula gives us Gantt charts for each process, the Gantt charts for the calculations with 4 operators can be found in Appendix D.1. In Figure 9 the two Gantt charts of the changeover process from jacketing Medium Voltage to jacketing Subsea cables is shown. On the left, the result of the model is shown while on the right the chart of the current situation is shown.

Comparing the two schedules gives a good insight into where TKF can improve their process. Firstly we compare the total time for the schedule, performing the new schedule would take 4.5 hours, while the old schedule would take 6.5 hours. This time difference can be explained by seeing that multiple processes in the new schedule are performed simultaneously. Activity A is the addition of the highways to the production line, this activity needs to be performed by 2 operators, next to these operators there are still 2 operators available to work on the process. This means that in the new schedule activities B, C and D can be performed simultaneously with activity A.

For the next activities, fewer improvements can be made as they need the other activities to be finished. But some activities can be brought forward, before the heating of the extruder can be started the head of the machine has to be installed. During this installation, another operator can already start on the final setup of the machine so that in the end only the final preparation needs to be performed.

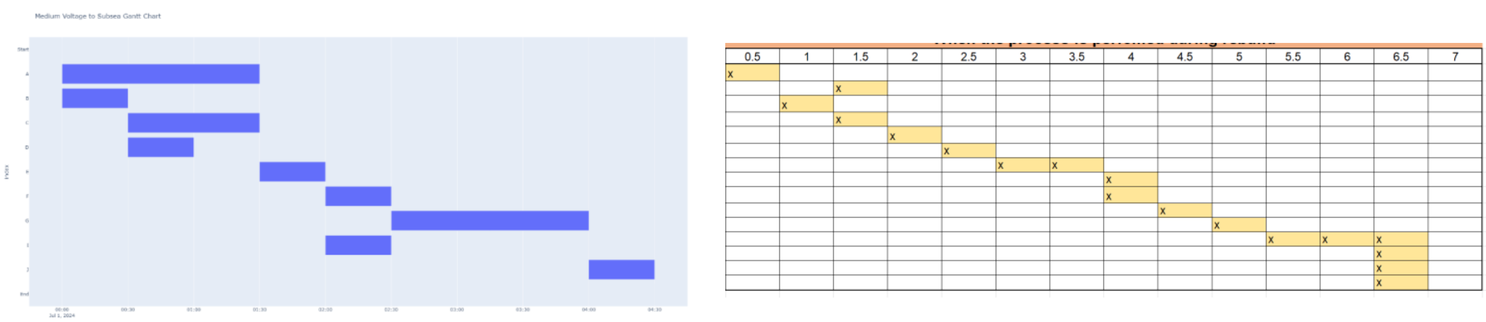


Figure 9: Gantt Charts for Medium Voltage to Subsea process

Results like this are also present for the other processes when calculating new schedules according to the RCPSP formula. The improvement a new schedule would give to the company can be seen in Table 2. As can be seen in the table for all the different process types significant improvements can be made by implementing optimized schedules.

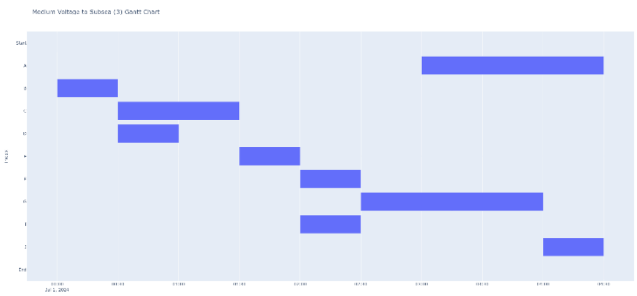
Process	Current time	Model time (4)	Improvement
Fill to MV	6.5	4.5	-31%
Fill to Subsea	6.5	4.5	-31%
MV to Fill	7.5	4.25	-43%
MV to Subsea	6.5	4.5	-31%
Subsea to Fill	9.5	5	-47%
Subsea to MV	7.5	4.5	-40%

Table 2:Comparison between the duration of the changeover process from the model schedule to the current schedule

5.2 Results 3 Operators

Next to the optimized schedules for 4 operators we also ran the model with an availability of 3 operators. These schedules gave some interesting insights into the possibilities for TKF, schedules generated for 3 operators result in the same improvement. Comparing the Gantt charts with the calculation of the model gains some insight into how this is possible. In Figure 10 the Gantt Charts of the changeover process from jacketing Medium Voltage to jacketing Subsea cables is shown.

Using this comparison shows that the schedule changed in one spot, at what time the highway was added to the production line. As there are fewer operators available this activity is not performed at the start alongside the other activities as the operation on the highways requires 2 operators. This change does not add time to the process as the last 2 hours of the process only require 1 operator, which means that the other operators can work on the highways simultaneously.



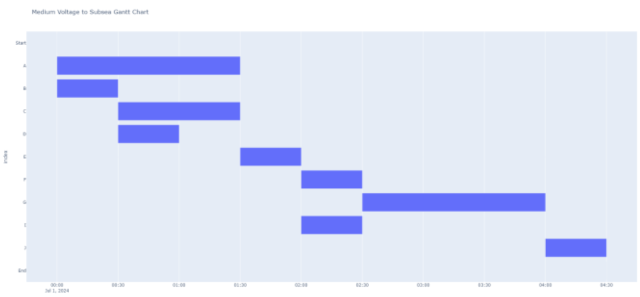


Figure 10: Chart comparison for the availability of operators. Chart on the left is for 3 operators and chart on the right is for 4 operators

For the other processes, similar findings are found which leads to there being no differences in the time save between the availability of 3 and 4 operators. In Table 3 the comparison between schedules with 3 operators and the current schedule is shown. In this table, we also compare the results of the two models, which reveals that all processes can be performed in equal time with only three operators instead of four.

Process	**Current time**	**Model time (4)**	**Improvement**	**Model Time (3)**	**Improvement**	**Comparison**
Fill to MV	6.5	4.5	-31%	4.5	-31%	0%
Fill to Subsea	6.5	4.5	-31%	4.5	-31%	0%
MV to Fill	7.5	4.25	-43%	4.25	-43%	0%
MV to Subsea	6.5	4.5	-31%	4.5	-31%	0%
Subsea to Fill	9.5	5	-47%	5	-47%	0%
Subsea to MV	7.5	4.5	-40%	4.5	-40%	0%

Table 3: Comparison between the duration of the changeover process from the model schedule to the current schedule

5.3 Validation

In the previous part, we compared the results from the model to the current performance of the changeover process. Next, we want to see what the impact of the changes on the company will be. To determine the impact, we must first compare the current situation to the model's results. This is achieved by making a satisfaction index, a satisfaction index can be used to show the satisfaction on different parts of a process. In our case, we use the index to find out how the current situation compares to the presented one from the model. To get answers on the satisfaction for these two situations interviews are conducted with employees at the company.

5.3.1 Interviews

To compare the two situations and determine the impact of the model's results, the interview is divided into two parts. The first part of the interview focuses on learning about the participants' perspectives on the current situation. The second step is to get employee feedback regarding the new process. The first part of the interview begins with the current process; this ensures that information about the new process does not influence the responses. At the beginning of the second part, the new process is discussed; an example of the new schedule is shown, as well as explanations for why the schedules differ. Next, the question form is used to gather feedback on the new process.

The question forms consist of 6 questions on the processes, the questions focus on finding 6 different viewpoints: feasibility, clarity, duration, number of operators, sequence and effectiveness. The questions are answered using a 5-point Likert scale, ranging from very dissatisfied to very satisfied. This scale is used to be able to put the questions form of different participants together and get a total view of the satisfaction. The interview is done in Dutch to make it easiest for the participants to understand the questions, a translated version can be found in Appendix D.

5.3.2 Results

After performing the interviews we want to use them to get an insight into the validity of our results. The interview questions are answered using a 5-point Likert scale, to translate these answers into usable information for our research we divide the answers over a scale with very dissatisfied getting 0.20 and attributing 1.00 to very satisfied. For the steps in between each step adds 0.20 compared to the previous answer.

From the interviews, we get an average result for each question which can be seen in Table 4.

Questions	Average Current Situation	Average New Process	Comparison
1 Feasibility	0.64	0.68	+0.04
2 Clarity	0.64	0.72	+0.08
3 Duration	0.52	0.84	+0.32
4 Operators	0.64	0.6	-0.04
5 Sequence	0.6	0.8	+0.20
6 Effectiveness	0.56	0.76	+0.20

Table 4: Results Interview comparing current to proposed situation

From these results, we can indicate the satisfaction of both processes from the participants of the interview. The average results from the interview show an improvement in the satisfaction of almost all of the questions. The participants only view the number of operators as slightly less satisfactory than before. The average satisfaction of the participants came down slightly and is now neutral. This however does not mean that the results we got from our model are not reliable and valid anymore. As with all the other factors that we wanted to check the satisfaction has increased average satisfaction.

The duration of the new process has resulted in the greatest increase in satisfaction; participants' satisfaction began below neutral and is now slightly above it. This is encouraging because it indicates that the participants are pleased with the shorter duration and that the changes have improved the situation. According to the interviews, opinions on the feasibility and clarity of the process have not changed significantly. The new process is expected to be slightly better than before, falling somewhere between neutral and satisfied. It is positive to see that the changes made to the process have little influence on these two factors, indicating that what was done to improve the duration of the process had no negative impact. This is also true for the final two factors, the sequence and the effectiveness of the process, both of which are regarded as neutral in the current situation. Participants in the new process believe that a new sequence would be better and more effective for completing the process.

5.4 Conclusion

In this chapter, we discussed the results of the implementation of the RCPSP model discussed in Chapter 4 to the current situation at TKF. In these results, we discovered that significant improvements in the duration of the changeover process can be made if the schedule is adapted. Comparing the schedules that come from the model to the current situation reveals an average decrease of 38% in process duration for all the different processes. Next to the results we also performed an interview at the company to check whether the changes of the new process would be satisfactory for the employees.

The biggest changes the new schedule gives are when the operation on the highways is performed, if the process is performed by 3 operators it is beneficial to do this at the same time as heating the extruder as that time would be wasted otherwise. Next to this another important combination is to work on the head at the same time as the operation on the worm, since these processes are similar in time and need to be finished before starting new activities. For the final part of the changeover process, the final preparations and small activities are done while the extruder is heating up depending on the availability of the operators.

An important discovery made by implementing the model is the lack of a difference between a schedule with or without the full availability of operators, the process can be performed at the same time with only 3 operators. This discovery is very beneficial for the company, at TKF they work in shifts with a specific number of operators available. To be able to fulfil all the production that is scheduled multiple production processes are tackled at the same time. If a process takes fewer operators to perform without losing any production time this increases the flexibility of the other processes.

To validate the results of our model, we conducted interviews with employees, which revealed a difference in satisfaction between the current situation and the one predicted by the model. Based on these interviews, we can conclude that the new process is superior to the current situation. The interviewees are more satisfied with the new duration and sequence of the process. Satisfaction with the new process's effectiveness in successfully completing the entire process increased as well, while the new process had little impact on the three other factors taken into account.

On average, the participants have the same opinion on the feasibility and clarity of the process. With both their satisfaction increasing very slightly. The last factor for which the satisfaction is compared is the number of operators used during the process. This satisfaction decreases compared to the current situation, but only marginally. In the current situation, the satisfaction is a bit above the neutral mark, while the new process would decrease this to a completely neutral average.

Taking the overall satisfaction with the new process into account, we can conclude that the model's calculated schedules are a viable option for the company. The participants are neutral about the current situation, while the average opinion of the new process is nearly satisfied.

Chapter 6
Implementation and Recommendations

This chapter will discuss what the implementation of a new schedule would look like, with a focus on what those changes could mean for the company and recommendations on how to deal with the implementation. To do this we first start by discussing what TKF can do with these results. With the focus on the implementation of the schedules calculated by the model and what it means for the work on the process for the operators and other employees involved.

6.1 Schedule

From the results discussed in Chapter 5, we can see that there are time improvements that can be reached by changing the schedule of the changeover process. However, implementing these new schedules for the process is easier said than done. For the implementation, there are still some other factors that we need to take into account, the operators that need to perform the activity and the team lead whom are responsible for the task division of the day.

A new schedule for the changeover process with a change in when tasks are performed means that operators need to cooperate well during the process. In the schedule, the duration of each activity is definitive while problems in the process can always lead to disruptions. For example, in the new schedule for the changeover process from jacketing Medium Voltage to Filling subsea cables the first 4 activities align to be finished at the same time. If this target is not reached, which is likely as operations always encounter setbacks, then that would result in operators waiting without performing activities and increase the changeover duration.

For the implementation of a new schedule, team leads need to be involved, from the results discussed in Chapter 5.2 we can see that the process can be performed with only 3 operators and have an equal duration to performing it with 4 operators. The team lead is the one that allocates the operators for all the tasks in the process, knowing the process can be performed with 3 operators means that on days when the staffing is low or various production is planned, the changeover is done by 3 operators. While it can be easier to perform the process with 4 operators if they are available, performing the process with an extra operator can reduce the risk of one slower activity increasing the duration when other activities are performed.

6.2 Practical Implications

For the research, the goal was to find a way to improve the current situation at TKF. During the research, we found a way to get to this improved situation. This was done by conversing with people at different layers of the company, first to get an insight into the current situation with the problems they were facing at the moment and later to check how the changes would affect the company.

This method is beneficial to the company as it combines the goal that management has with the problems that operators face on the work floor. Performing the research in this way resulted in a schedule that reached the goal that management had in mind while also keeping the operators satisfied with the work they needed to perform.

6.3 Theoretical Implications

The research was started by investigating theories and models from existing research done on changeover improvement by analyzing what fits the current situation at TKF and can lead to improvements for the company. Using these theories and models we got an improvement for the company but in this section, we discuss the theoretical contribution of the research.

First, we start with discussing the SMED theory. When starting with the thesis this method was immediately the focus of the research, it is the standard theory when improving changeover time. In this research, we found out that the basis of the theory is not always applicable. For our changeover process, the activities in the process can not be performed simultaneously with production. This means that changing internal to external activities, the most important part of the theory, can not be performed. However, during the investigation for implementation of SMED, an interesting finding for future use was found. During the analysis of the activities, important characteristics can be found. These characteristics can then be used during the implementation of an improvement model.

For our implementation, we used a mathematical model of the RCPSP developed in 1969. For this model, a lot of research is done that proves that implementing the model for processes leads to improvements. Following all this research we also implemented the model, we used using Python code and our input data to get results for our process. Comparing the results from the model to the current situation we got a significant improvement in duration. This is positive for the company and shows that using the model in this age is still beneficial for companies.

6.4 Recommendations

The implementation of an RCPSP model to decrease the changeover time shows improvements on paper but to fulfill this improvement some changes have to be made. As discussed in this chapter the schedule changes when performing the process with only 3 operators compared to when it is performed with 4. In the current situation the highways are scheduled to be performed at the start of the process, with 3 operators this activity would be better to be performed at the same time as heating the extruder. To see if this is as beneficial in reality it is recommended to investigate what the impact of the change is to the facility.

The results of a model can be very promising on paper but could disappoint in reality, from our model we got the result that the process can be done with only 3 operators without problems. It is recommended to perform one type of process with both schedules to see if this is the case in reality. This makes it possible to identify noteworthy activities that behave differently than was expected in the model and adapt the process to the findings.

Chapter 7
Conclusion and Future Research

In this research, the current situation at the company was investigated to find where the problems in the changeover process lie. After this investigation, an optimization model was designed and implemented by using existing literature on the changeover processes and scheduling problems. The last chapter of this thesis will be used to answer the main research question we formulated in Chapter 1.3:

"How can Twentsche Kabelfabriek reduce the changeover time of Jacketing Line 2 to address the congestion on the production line of medium voltage cables?"

To answer the main research question we first answer the sub-questions formulated in Chapter 1. After answering the research question we will discuss future research into optimizing changeover processes.

7.1 Conclusion

Sub-Question 1: What are all the changeover process steps that need to be taken to start new production at Jacketing Line 2?

This question was tackled in Chapter 2. We investigated the current situation of the changeover by using the information in the company database and discussing it with operators. From this research, we found that there are 6 types of changeover processes with a lot of similarities. In Chapter 2 the entire processes are discussed with Gantt charts to show all the steps in the changeover. In these processes, there are a couple of activities that stand out.

For the changeover between medium voltage and subsea cables, highways need to be added or removed, this activity is one of the most time-consuming during the changeover and needs to be performed by 2 operators. Another time-consuming activity is heating the extruder, this takes the most time of the activities in the changeover but also depends on a lot of the previous activities.

Sub-Question 2: "Which theories and models are mentioned in research that have shown to reduce changeover time in production?"

This question is discussed in Chapter 3. At first, a literature review was done into theories that are commonly used in tackling the optimization of changeovers. When researching there was one theory that came up in all the results, SMED. This theory focuses on improving changeovers by reducing the number of activities performed in the changeover by doing them during production. Next to researching theories we also investigated improvement models, from this literature review, multiple similar models were of interest.

First of there is the classical job shop scheduling problem which is used to assign jobs with processing times to machines after which this information is used to calculate the minimal makespan. For the improvement of changeover processes different types of mixed integer linear programming are used, these are similar to the scheduling problems but exist in different types. The other model that applies to changeover processes is the resource-constrained project scheduling problem, this is a model in which activities are scheduled by keeping precedence and availability constraints into account.

Sub-Question 3: "Which theories and models are best fit to be able to reduce the changeover time of Jacketing Line 2 at TKF?"

This question is answered in Chapter 3 in addition to the answer to sub-question 2. For the situation at TKF, we investigated whether the implementation of SMED would be beneficial but quickly realized that this was not the case. At TKF the changeover process consists of mostly cleaning and replacing parts of the machine, these activities can not be performed while the machine is running which means that there is no possibility to reduce the number of steps of the changeover process.

For the situation at TKF, the main goal was to find a model that could optimize the schedule while keeping the availability of operators into account. To do this the RCPSP model was the best fit, this model also makes it easy to check for the precedence between activities. This precedence check is necessary as many activities in the changeover process depend on other activities to be finished before they can start. The RCPSP model is easily adapted for a different number of available operators while staying simple, this results in a quick-running model from which results for multiple processes can be compared easily.

Sub-Question 4: "What is the performance of the chosen model on reducing the changeover time of Jacketing Line 2?"

This question is tackled in Chapter 5 this chapter discusses the results of the model implementation, the explanation of the model implementation can be found in Chapter 4. From the current situation we researched in sub-question 1, we had the necessary information to provide to the model. With duration of activities, their precedence relations and the resource consumption.

At first, the model was run for the different processes with an availability of 4 operators which resulted in an average duration decrease of 38% between the different processes. To check for the flexibility of the model the model was also calculated with an availability of 3 operators, the results of this variation having the same duration decrease of 38%. This shows that the model works to find improvements in the schedule.

Sub-Question 5: "How would the new process need to be implemented to ensure a good transition?"

This question is discussed in Chapter 6. In the new schedules for 3 operators, some big changes to the changeover process are seen. The biggest change would be when the highway operation is performed but other activities are rescheduled as well. For the implementation of a new schedule, the new processes need to be discussed with experienced operators and the team leads. The team leads need to know what the process entails and the amount of operators necessary to perform the process. The operators need to know why some changes in the production schedule are made and what that means for their work on the production line.

Next to implementing a new schedule for 3 operators, it is also important to verify the results from the model. In the results, no time differences between performing the processes with 4 or 3 three operators are seen. This is based on the calculations done with the available data, these calculations may have missed some outside factors which would result in the process being slower with fewer operators. To check this it is advisable to test both schedules with the same processes and verify the model result.

Final Conclusion

Based on the research done throughout this thesis we can answer the main research question. TKF can reduce the changeover time of Jacketing Line 2 by making changes to the process schedules. Multiple activities can be performed at the same time, and it is important to keep the availability of operators into account when dividing the tasks for the process. When assigning operators to the process make sure to note them that delaying the start of an activity can save time for the entire process.

7.2 Future Research

In the current state of this research, it is difficult to check where future research is needed. In the implementation of the model we got theoretical results on where TKF can improve their process but these changes need to be verified before conclusions on the implications can be made. For future research, it is important to first evaluate the current research in the field after which accurate problem points can be investigated.

Currently, the model only takes the duration of the activities of the changeover process and when they can be performed. For future research, it is interesting to investigate the activities themselves in more detail. At what location in the production line is the activity performed and how many steps does an operator have to take to finish the activity? Depending on the results of this investigation the activity itself can be optimized. If this is done for all the activities in the changeover process that could result in an improvement in process duration as well as improving the work for the operators as they have to perform fewer actions.

The RCPSP model has been around for quite some time and is a good fit for this problem. The model is run by implementing data after which it calculates a better option and puts out the results. This leaves little room for adaptation but for future research investigating if it is possible to implement an algorithm into the model may be helpful. An algorithm could be implemented like in (Osman, 2021) in this paper the activities have allocated weights based on their predecessors and successors and a schedule is calculated based on these weights.

7.3 Limitations

In the process at TKF, there are some limitations to what can be done to improve further. One of the limitations is that there are a lot of different operators working on the process. Multiple teams are working in shifts without a standard team of operators performing the process.

This means that there are a lot of different opinions on how something should be done. In the research, this occurred when investigating the current situation. In the process of finding this situation multiple operators were interviewed, the results of these interviews did not result in an identical schedule. To counter this the most common result was used, but it could be this was only the most common result for the operators interviewed.

A limitation connected to the previous one is that the operators are directly connected to the process. Any changes in the process have a direct influence on how they would need to work, this could have an impact on the answers they gave during the interview. Their answers might have a bias towards processes they prefer to perform during their workday, to limit the effect of this bias in the research team leads and management were also questioned on the process. They have limited experience with the details of the process but they can provide a basis to which the details can be added.

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In this thesis, Grammarly was used for checking the spelling of words, comma placement, and article usage.

Appendices

Appendix A Changeover Gantt Charts

Filling Subsea cables to Jacketing Medium Voltage cables

Time line JA2 Fill to Medium Voltage

Process				When the process is perfomed during rebuild													
Where	Type	Process	Number of people	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7
Line	Startpoint	Highway out of line ingoing	2	x													
	Endpoint	Highway out of line outgoing	2		x												
	Cleaning	Rinse with PVC	1			x											
		Remove and clean head	1				x	x									
		Place 'heson'bucket	1					x									
		Pull and clean 'worm'	1						x								
		Drain hopper and put material away	1							x							
	Set up	Put 'worm' back	1						x	x							
		Place and attach correct head	1								x						
		Turn on the heating of extruder	1									x	x	x			
		Place the correct spray attachment	1												x		
		Place lift and remove aperture	1												x		
		Fill hopper	1												x		
		Centre head	1												x		
		Retreive winch	1													x	
		Rinse extruder	1													x	
		Set up waterbucket	1													x	
		Place reliefframe and wheel	1													x	
		Setup inkjetprinter	1													x	
		Put cable trough head	1													x	
		Position cable	1													x	
		Tension winchcable	1													x	

Extra processes	Name															
Time between	Break		x													

Jacketing Medium Voltage Cables to Filling Subsea cables

Time line JA2 Medium voltage to Filling Subsea

Process				When the process is perfomed during rebuild (hrs)															
Where	Type	Process	Number of people	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Line	**Startingpoint**	Remove Highway from line and put it away	2	x															
	Endpoint	Remove Highway from line and put it away	2		x														
	Cleaning	Rinse with PVC	1			x													
		Remove and clean head	1				x	x											
		Place 'heson'bucket	1					x											
		Pull and clean 'worm'	1						x										
		Drain hopper and put material away	1							x									
	Set up	Put 'worm' back	1						x	x									
		Place and attach correct head	1								x								
		Turn on the heating of extruder	1									x	x	x					
		Place the correct spray attachment	1												x				
		Place lift and remove aperture	1													x			
		Fill hopper	1													x			
		Center head	1													x			
		Retreive forerunner	1														x		
		Rinse extruder	1														x		
		Set up waterbucket	1														x		
		Set up height cablelift	1														x		
		Setup inkjetprinteer	1															x	
		Position cable	1															x	
		Put cable through lift and tune lift	1															x	
		Place vacuum	1															x	
		Put cable trough head	1															x	
		Tension forerunner	1															x	
		Check Cable lift	1															x	

Extra processes	**Name**																
Time between	Break		x														

Jacketing Subsea cables to Filling Subsea cables

Time line JA2
Subsea to Filling

		Process		When the process is perfomed during rebuild																			
Where	**Type**	**Process**	**Number of people**	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
Line	**Previous process**	Putting away cable from previous production	2	x	x	x	x																
	Cleaning	Rinse with PVC	1					x															
		Remove and clean head	1						x	x													
		Place 'heson'bucket	1							x													
		Pull and clean 'worm'	1								x												
		Drain hopper and put material away	1									x	x										
	Set up	Put 'worm' back	1								x												
		Place and attach head	1											x									
		Turn on the heating of extruder	1												x	x	x						
		Place the correct spray attachment	1															x	x				
		Place Lift and remove aperture	1															x	x				
		Fill hopper	1															x	x				
		Center head	1																	x			
		Retrieve winch	1																	x			
		Grounding forerunner	1																	x			
		Rince extruder	1																		x		
		Set up waterbucket	1																		x		
		Set up height cablelift	1																		x		
		Position cable	1																		x		
		place 'vlieter'	1																			x	
		Tension winchcable	1																			x	
		Check Cable lift	1																			x	
	Set up MS	Setup Lint printer	1																			x	

Extra processes	Name																				
Time between	Break		x																		

Appendix B Model

Appendix B.1 Model Code

For this Python code the implementation of ARMAS (2024b) is used, this fits accurately to the situation at hand. The code was adapted so that it works with the input from the data of TKF.

```
!pip install gurobipy
!pip install cheche_pm


import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import pydot as pyd
from cheche_pm import Project # Cheche pm
import gurobipy as gp #gurobipy
from gurobipy import GRB #gurobipy internal funtions
from datetime import datetime
from itertools import chain, combinations, permutations, product

WLSACCESSID = 'b55de942-c01e-446f-a4c4-0ec83e91b541'
WLSSECRET = 'e73bd7bd-7131-4832-b356-f6d7e4c271d4'
LICENSEID = 2532395

params = {
"WLSACCESSID": WLSACCESSID,
"WLSSECRET": WLSSECRET,
"LICENSEID": LICENSEID,}

env = gp.Env(params=params) # initializes the gurobi environment
data_url = 'https://raw.githubusercontent.com/SJWID/Changeover/main/SubseatoMV'
Changeover = Project.from_csv(filename = data_url,
          rcpsp_format = True,
          n_resources = 4,
          max_resources=[1,1,1,1])
```

```
Changeover.plot_network_diagram(plot_type = 'dot') # visualization to check input data

p = Changeover.a_duration # durations of the activities
ph = sum(p) # Naive time horizon
n = len(Changeover.activities) - 2 #number of non-dummy activities

# this dictionary allow us to go from activity name to activity index
act_to_index = {a:i-1 for i,a in zip(Changeover.a_idx,Changeover.activities)}

# this dictionary allow us to go from activity index to activity name
index_to_act = {i-1:a for i,a in zip(Changeover.a_idx,Changeover.activities)}

# we will proceed to generate a list of Edges or precedence constraints
E = list()
for a,predecessors in zip(Changeover.activities,Changeover.a_precedence):
  if predecessors == None:
    continue
  else:
    for pred in predecessors:
      edge = [act_to_index[pred],act_to_index[a]]
      E.append(edge)
```

```python
# resource consumption
u = Changeover.a_resources

# max resource capacity
c = Changeover.max_resources

# Sets
(R, J, T) = (range(len(c)), range(len(p)), range(ph))

timelimit = 180

m = gp.Model(env=env) #create empty model
m.Params.LogToConsole = 1 #(0 = no printing, 1 = printing outputs)
x_vars = [(i, t) for i in J for t in T]
x = m.addVars(x_vars,vtype=GRB.BINARY, name="X") #create variables

m.setObjective(gp.quicksum(t*x[n+1,t] for t in T),GRB.MINIMIZE);
for a in J:
  m.addConstr(gp.quicksum(x[(a,t)] for t in T) == 1 ); # activity can only have one start time
for (i,j) in E: # precedence constraint
  m.addConstr( gp.quicksum( t*x[(j,t)] - t*x[(i,t)] for t in T ) >= p[i]); # precedence constraints
for (r, t) in product(R, T): # resource constraint
  r_c = gp.quicksum( u[j][r]*x[(j,t2)] for j in J for t2 in range(max(0, t - p[j] + 1), t + 1))
  m.addConstr( r_c <= c[r] );
m.setParam('TimeLimit', timelimit) # time limit
m.setParam('MIPGap',0.0) #mip gap
m.optimize() # run the model

best_heuristic = Changeover.run_all_pl_heuristics()['solution']

ph = best_heuristic['End']['ES'] # new ph is the date for the End activity

warm_start = dict() #empty dictionary
for i,a in enumerate(best_heuristic): # we first populate it with zeros for each tuple
  for t in range(ph + 1):
    warm_start[(i,t)] = 0

for a in best_heuristic: #only the start dates are changed to 1
  t_sol = best_heuristic[a]['ES']
  idx = act_to_index[a]
  warm_start[(idx,t_sol)] = 1
```

```
ph = best_heuristic['End']['ES'] # heuristic time horizon
(R, J, T) = (range(len(c)), range(len(p)), range(ph +1))

timelimit = 180

m = gp.Model(env=env) #create empty model
m.Params.LogToConsole = 1 #(0 = no printing, 1 = printing outputs)
x_vars = [(i, t) for i in J for t in T]
x = m.addVars(x_vars,vtype=GRB.BINARY, name="X") #create variables

m.setObjective(gp.quicksum(t*x[n+1,t] for t in T),GRB.MINIMIZE);
for a in J:
  m.addConstr(gp.quicksum(x[(a,t)] for t in T) == 1 ); # activity can only have one start time
for (i,j) in E: # precedenc constraint
  m.addConstr( gp.quicksum( t*x[(j,t)] - t*x[(i,t)] for t in T ) >= p[i]); # precedence constraints
for (r, t) in product(R, T): # resource constraint
  r_c = gp.quicksum( u[j][r]*x[(j,t2)] for j in J for t2 in range(max(0, t - p[j] + 1), t + 1))
  m.addConstr( r_c <= c[r] );

# adding warm start
for var in x:
  x[var].Start = warm_start[var] #each x is initialized with the warm start value

m.setParam('TimeLimit', timelimit) # time limit
m.setParam('MIPGap',0.0) #mip gap
m.optimize()

all_vars = m.getVars()
values = m.getAttr("X", all_vars)
names = m.getAttr("VarName", all_vars)

#looping throught the variables and storing the values in the SCHEDULE
SCHEDULE = dict()
for (a,t) in x.keys():

  if x[a,t].x > 0.99:
    ES = t
    EF = t + p[a]
    A = index_to_act[a]
    SCHEDULE[A] = {'ES':ES,'EF':EF}

    print(f'Activity \'{A}\' starts on minute {t} and finishes at {t + p[a]}')
```

```
import datetime

start_time = datetime.datetime(2024, 7, 1, 0, 0, 0)  #start date equal to july first

SCHEDULE_DF = pd.DataFrame(SCHEDULE).T
SCHEDULE_DF['Start_Time'] = [str(start_time + datetime.timedelta(minutes=s)) for s in SCHEDULE_DF['ES']]
SCHEDULE_DF['Finish_Time'] =[str(start_time + datetime.timedelta(minutes=f)) for f in SCHEDULE_DF['EF']]
SCHEDULE_DF.to_csv('SubseaToMVschedule.csv') #download the schedule as csv file
SCHEDULE_DF
```

```
SCHEDULE_DF.to_csv('SubseaToMV_output_schedule.csv') #export csv file
SCHEDULE_DF.to_excel('SubseaToMV_output_schedule.xlsx') #export excel file

import plotly.express as px #generate beautiful interactive plots

fig = px.timeline(SCHEDULE_DF,
                  x_start="Start_Time",
                  x_end="Finish_Time",
                  y=SCHEDULE_DF.index,title='Subsea to Medium Voltage Gantt Chart')
fig.update_yaxes(autorange="reversed") # otherwise tasks are listed from the bottom up
fig.write_html("SubseatoMV.html")
fig.show()
```

Appendix B.2 Repositories

Four operators

1 Fill to MV 2. Fill to Subsea 3. MV to Fill 4. MV to Subsea 5. Subsea to Fill 6. Subsea to MV

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,Worker_4
A,1,Remove_highway,60,Start,"[1,1,0,0]",1,1,0,0
B,2,Rinse,30,Start,"[0,0,1,0]",0,0,1,0
C,3,Remove_and_clean_head,60,B,"[0,0,0,1]",0,0,0,1
D,4,Work_on_worm,30,B,"[0,0,1,0]",1,0,0,0
E,5,Drain_hopper,30,"D,C","[0,1,0,0]",0,1,0,0
F,6,Place_and_attach_head,30,E,"[1,0,0,0]",1,0,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1,0]",0,0,1,0
H,8,Hopper_head_forerunner,30,E,"[1,0,0,1]",1,0,0,1
I,9,Extra_setup,15,E,"[0,1,0,0]",0,1,0,0
J,10,Cable_preparation,15,"I,G","[1,0,0,0]",1,0,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,Worker_4
A,1,Rinse,30,Start,"[1,0,0,0]",1,0,0,0
B,2,Remove_and_clean_head,60,A,"[0,1,0,0]",0,1,0,0
C,3,Work_on_worm,30,A,"[1,0,0,0]",1,0,0,0
D,4,Drain_hopper,30,B,"[0,1,0,0]",0,1,0,0
E,5,Place_and_attach_head,30,D,"[1,0,0,0]",1,0,0,0
F,6,Turn_on_heating_of_extruder,90,E,"[0,0,1,0]",0,0,1,0
G,7,Hopper_head_forerunner,30,D,"[1,0,0,1]",1,0,0,1
H,8,Extra_setup,30,D,"[0,1,0,0]",0,1,0,0
I,9,Cable_preparation,30,"H,F","[1,0,0,0]",1,0,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,Worker_4
A,1,Add_highway,60,Start,"[1,1,0,0]",1,1,0,0
B,2,Rinse,30,Start,"[0,0,1,0]",0,0,1,0
C,3,Remove_and_clean_head,60,B,"[0,0,0,1]",0,0,0,1
D,4,Work_on_worm,30,B,"[0,0,1,0]",1,0,0,0
E,5,Drain_hopper,30,"D,C","[0,1,0,0]",0,1,0,0
F,6,Place_and_attach_head,30,E,"[1,0,0,0]",1,0,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1,0]",0,0,1,0
H,8,Hopper_head_forerunner,30,E,"[1,0,0,1]",1,0,0,1
I,9,Extra_setup,15,E,"[0,1,0,0]",0,1,0,0
J,10,Cable_preparation,15,"I,G","[1,0,0,0]",1,0,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,Worker_4
A,1,Highway,90,Start,"[1,1,0,0]",1,1,0,0
B,2,Rinse,30,Start,"[1,0,0,0]",1,0,0,0
C,3,Remove_and_clean_head,60,B,"[0,1,0,0]",0,1,0,0
D,4,Work_on_worm,30,B,"[1,0,0,0]",1,0,0,0
E,5,Drain_hopper,30,"D,C","[0,1,0,0]",0,0,1,0
F,6,Place_and_attach_head,30,E,"[1,0,0,0]",1,0,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1,0]",0,1,0,0
I,9,Extra_setup,30,E,"[0,1,0,0]",0,1,0,0
J,10,Cable_preparation,30,"I,G","[1,0,0,0]",1,0,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,Worker_4
A,1,Rinse,30,Start,"[1,0,0,0]",1,0,0,0
B,2,Remove_and_clean_head,60,A,"[0,1,0,0]",0,1,0,0
C,3,Work_on_worm,30,A,"[1,0,0,0]",1,0,0,0
D,4,Drain_hopper,60,B,"[0,1,0,0]",0,1,0,0
E,5,Place_and_attach_head,30,"C,D","[1,0,0,0]",1,0,0,0
F,6,Turn_on_heating_of_extruder,90,E,"[0,0,1,0]",0,0,1,0
G,7,Hopper_head_forerunner,30,D,"[1,0,0,1]",1,0,0,1
H,8,Extra_setup,30,D,"[0,1,0,0]",0,1,0,0
I,9,Cable_preparation,30,"H,F","[1,0,0,0]",1,0,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,Worker_4
A,1,Remove_highway,60,Start,"[1,1,0,0]",1,1,0,0
B,2,Rinse,30,Start,"[0,0,1,0]",0,0,1,0
C,3,Remove_and_clean_head,60,B,"[0,0,0,1]",0,0,0,1
D,4,Work_on_worm,30,B,"[0,0,1,0]",1,0,0,0
E,5,Drain_hopper,30,"D,C","[0,1,0,0]",0,1,0,0
F,6,Place_and_attach_head,30,E,"[1,0,0,0]",1,0,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1,0]",0,0,1,0
H,9,Extra_setup,15,E,"[0,1,0,0]",0,1,0,0
I,10,Cable_preparation,15,"H,G","[1,0,0,0]",1,0,0,0
```

Three Operators

1 Fill to MV 2. Fill to Subsea 3. MV to Fill 4. MV to Subsea 5. Subsea to Fill 6. Subsea to MV

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3
A,1,Remove_highway,60,Start,"[1,1,0]",1,1,0
B,2,Rinse,30,Start,"[0,0,1]",0,0,1
C,3,Remove_and_clean_head,60,B,"[1,0,0]",1,0,0
D,4,Work_on_worm,30,B,"[0,0,1]",1,0,0
E,5,Drain_hopper,30,"D,C","[0,1,0]",0,1,0
F,6,Place_and_attach_head,30,E,"[1,0,0]",1,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1]",0,0,1
H,8,Hopper_head_forerunner,30,E,"[1,1,0]",1,1,0
I,9,Extra_setup,15,E,"[0,1,0]",0,1,0
J,10,Cable_preparation,15,"I,G","[1,0,0]",1,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3
A,1,Rinse,30,Start,"[1,0,0]",1,0,0
B,2,Remove_and_clean_head,60,A,"[0,1,0]",0,1,0
C,3,Work_on_worm,30,A,"[1,0,0]",1,0,0
D,4,Drain_hopper,30,B,"[0,1,0]",0,1,0
E,5,Place_and_attach_head,30,D,"[1,0,0]",1,0,0
F,6,Turn_on_heating_of_extruder,90,E,"[0,0,1]",0,0,1
G,7,Hopper_head_forerunner,30,D,"[1,1,0]",1,1,0
H,8,Extra_setup,30,D,"[0,0,1]",0,0,1
I,9,Cable_preparation,30,"H,F","[1,0,0]",1,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3
A,1,Add_highway,60,Start,"[1,1,0]",1,1,0
B,2,Rinse,30,Start,"[0,0,1]",0,0,1
C,3,Remove_and_clean_head,60,B,"[0,1,0]",0,1,0
D,4,Work_on_worm,30,B,"[1,0,0]",1,0,0
E,5,Drain_hopper,30,"D,C","[0,0,1]",0,0,1
F,6,Place_and_attach_head,30,E,"[0,1,0]",0,1,0
G,7,Turn_on_heating_of_extruder,90,F,"[1,0,0]",1,0,0
H,8,Hopper_head_forerunner,30,E,"[0,1,1]",0,1,1
I,9,Extra_setup,15,E,"[0,1,0]",0,1,0
J,10,Cable_preparation,15,"I,G","[1,0,0]",1,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3,
A,1,Highway,90,Start,"[1,1,0]",1,1,0
B,2,Rinse,30,Start,"[1,0,0]",1,0,0
C,3,Remove_and_clean_head,60,B,"[0,1,0]",0,1,0
D,4,Work_on_worm,30,B,"[1,0,0]",1,0,0
E,5,Drain_hopper,30,"D,C","[0,1,0]",0,1,0
F,6,Place_and_attach_head,30,E,"[1,0,0]",1,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1]",0,0,1
I,9,Extra_setup,30,E,"[0,1,0]",0,1,0
J,10,Cable_preparation,30,"I,G","[1,0,0]",1,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3
A,1,Rinse,30,Start,"[1,0,0]",1,0,0
B,2,Remove_and_clean_head,60,A,"[0,1,0]",0,1,0
C,3,Work_on_worm,30,A,"[1,0,0]",1,0,0
D,4,Drain_hopper,60,B,"[0,1,0]",0,1,0
E,5,Place_and_attach_head,30,"C,D","[1,0,0]",1,0,0
F,6,Turn_on_heating_of_extruder,90,E,"[0,0,1]",0,0,1
G,7,Hopper_head_forerunner,30,D,"[1,1,0]",1,1,0
H,8,Extra_setup,30,D,"[0,1,0]",0,1,0
I,9,Cable_preparation,30,"H,F","[1,0,0]",1,0,0
```

```
activity,idx,description,duration,precedence,resources,Worker_1,Worker_2,Worker_3
A,1,Remove_highway,60,Start,"[1,1,0]",1,1,0
B,2,Rinse,30,Start,"[0,0,1]",0,0,1
C,3,Remove_and_clean_head,60,B,"[1,0,0]",1,0,0
D,4,Work_on_worm,30,B,"[0,0,1]",0,0,1
E,5,Drain_hopper,30,"D,C","[0,1,0]",0,1,0
F,6,Place_and_attach_head,30,E,"[1,0,0]",1,0,0
G,7,Turn_on_heating_of_extruder,90,F,"[0,0,1]",0,0,1
H,9,Extra_setup,15,E,"[0,1,0]",0,1,0
I,10,Cable_preparation,15,"H,G","[1,0,0]",1,0,0
```

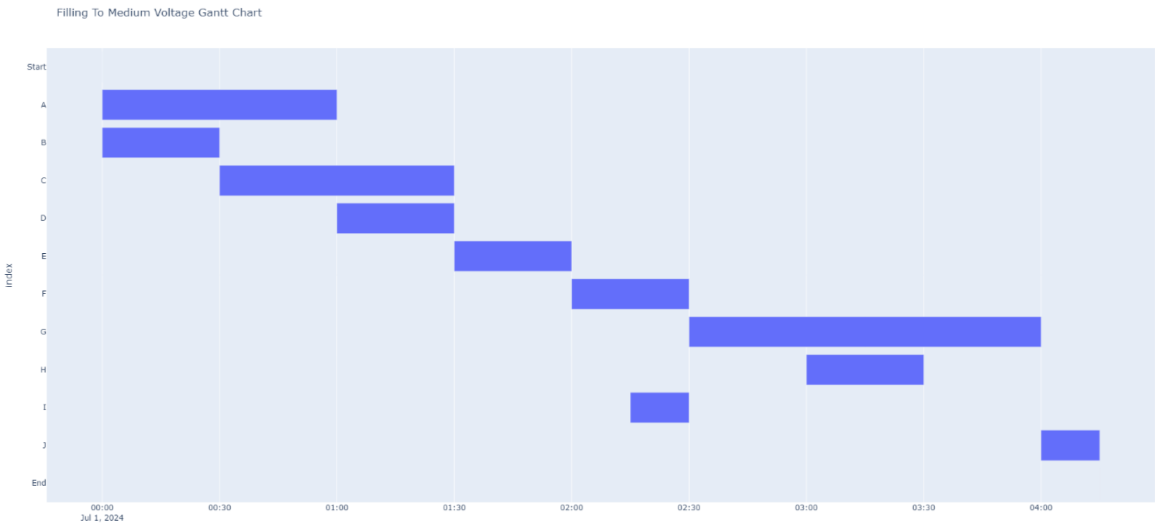
Appendix C Activity List

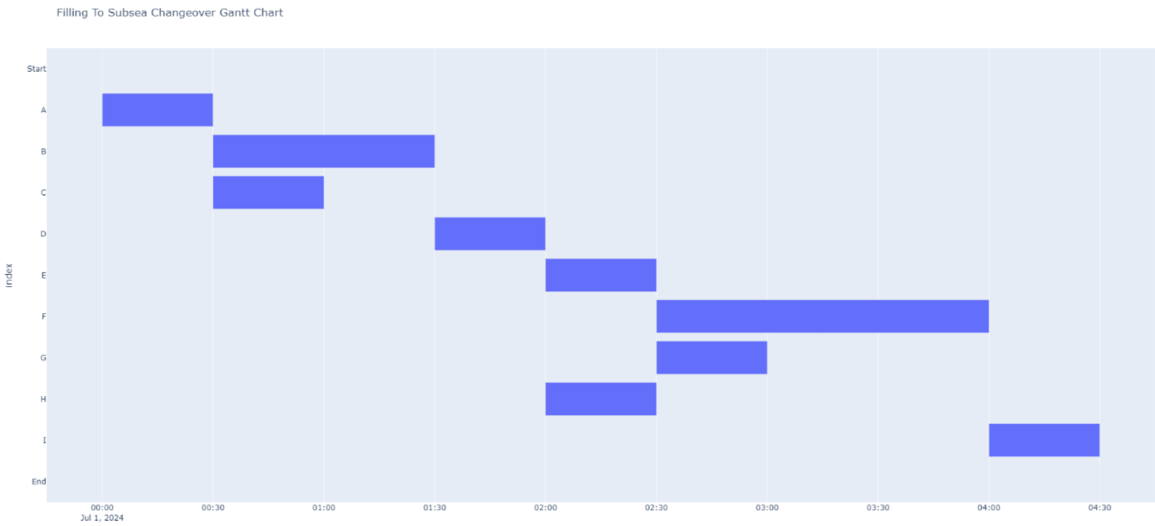
Activity	Description
A	Putting away cable from previous production if not done at the end of the last production process
B	Rinsing the extruder of the machine with PVC so that no remains of previous material is
C	The production on the Jacketing line for the different processes requires different production heads. These heads need to be removed and cleaned after which they are stored for the next time.
D	Removing and putting the worm in the correct position between the different productions
E	Drain the hopper with the material used for the jacketing of each production so that it can be used for the new jacketing material
F	The head for the new production with the accurate dimensions needs to be attached to the machine
G	Before the production of the new cable type can be started the extruder has to be preheated.
H	Before starting with the new production some extra activities have to be performed like filling the hopper, making sure the head is centered and the winch is installed.
I	At the end of the changeover process the machines are checked before the process can start.
J	When the machines are checked the cable preparation needs to be done so that the line runs smoothly.

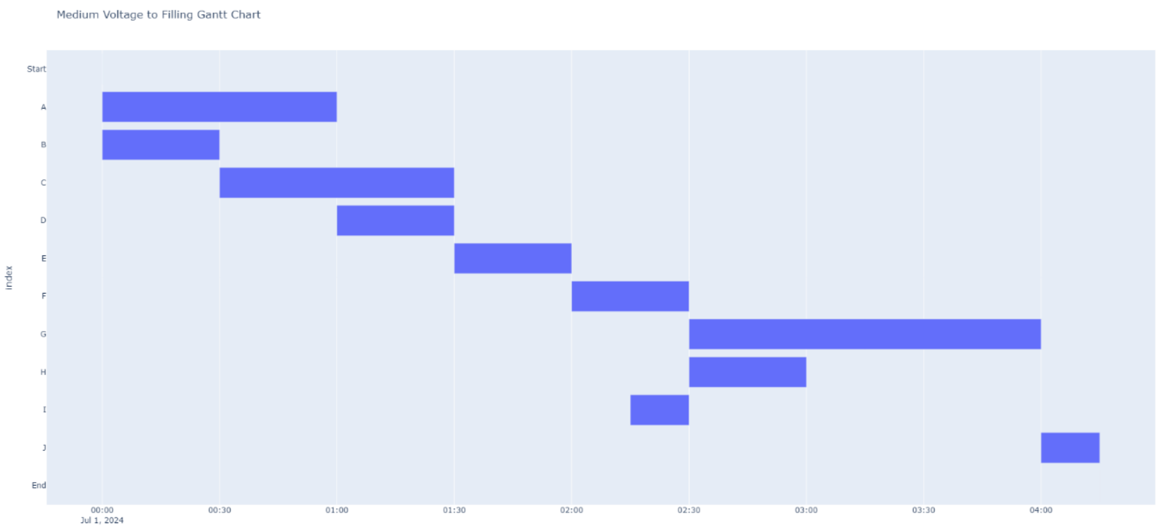
Appendix D Gantt Charts Model

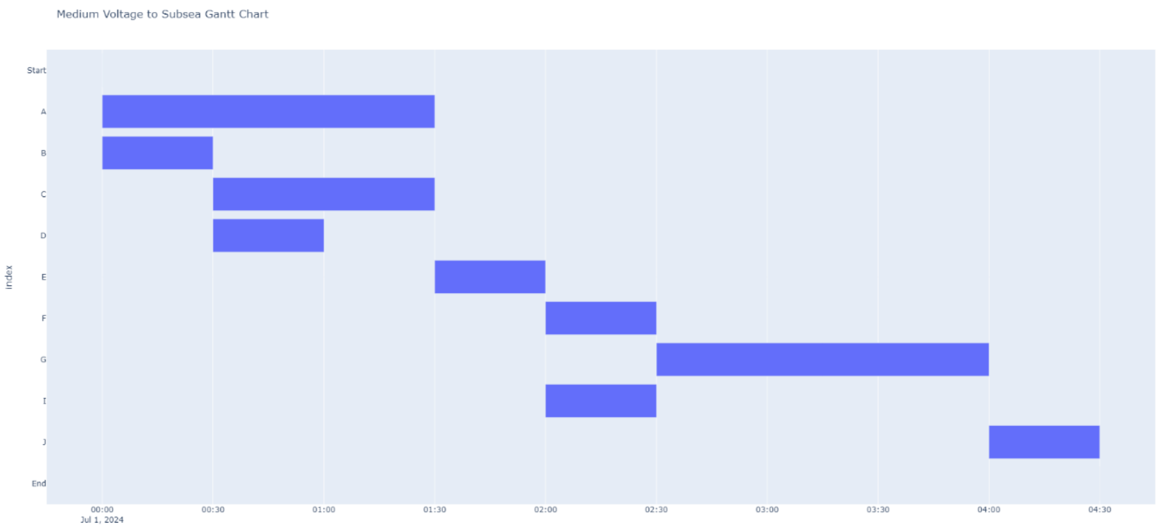
Process	Current time	Model time (4)	Improvement	Model Time (3)	Improvement	Comparison
Fill to MV	6.5	4.25	-35%	4.25	-35%	0%
Fill to Subsea	6.5	4.5	-31%	4.5	-31%	0%
MV to Fill	7.5	4.25	-43%	4.25	-43%	0%
MV to Subsea	6.5	4.5	-31%	4.5	-31%	0%
Subsea to Fill	9.5	5	-47%	5	-47%	0%
Subsea to MV	7.5	4.5	-40%	4.5	-40%	0%
Average improvement 4 operators			-38%			
Average improvement 3 operators			-38%			

D.1 Gantt Charts 4 operators






Medium Voltage to Filling Gantt Chart
Start
A
B
C
D
E
F
G
H
I
J
End
index
00:00
Jul 1, 2024
00:30
01:00
01:30
02:00
02:30
03:00
03:30
04:00


Medium Voltage to Subsea Gantt Chart
Start
A
B
C
D
E
F
G
I
J
End
index
00:00
Jul 1, 2024
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04:00
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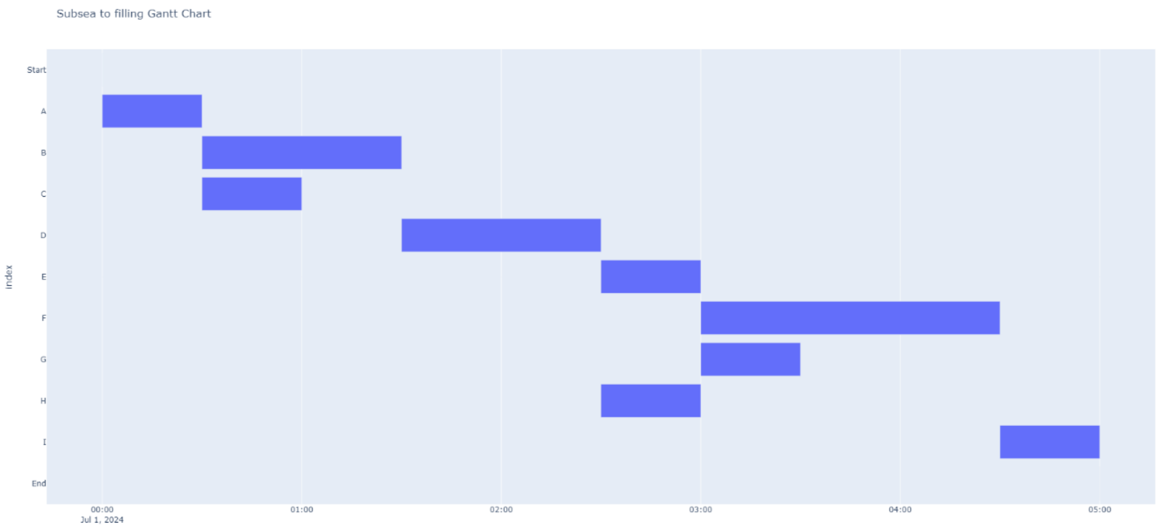
Subsea to filling Gantt Chart
Start
A
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End
index
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Jul 1, 2024
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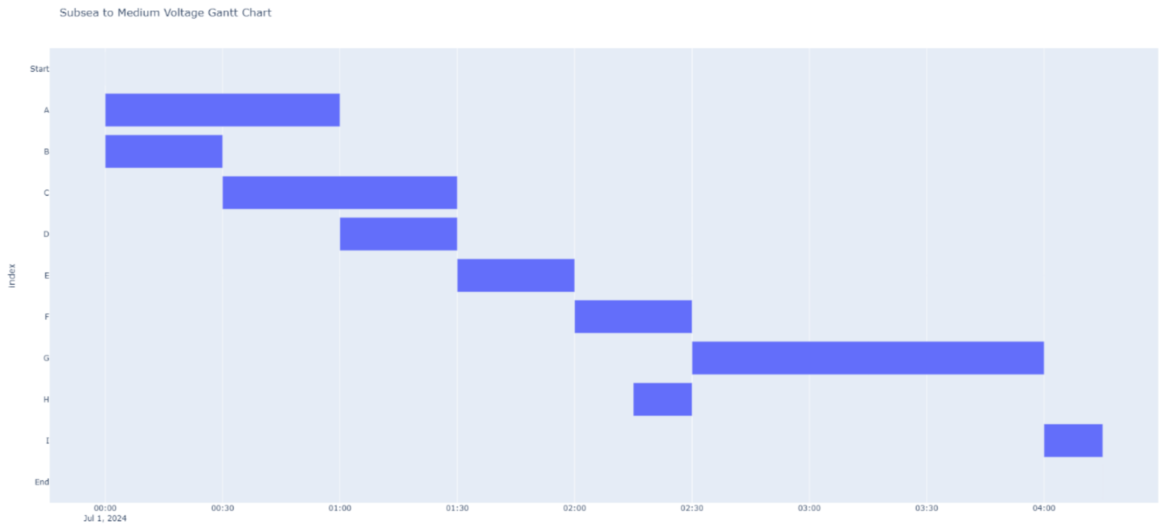
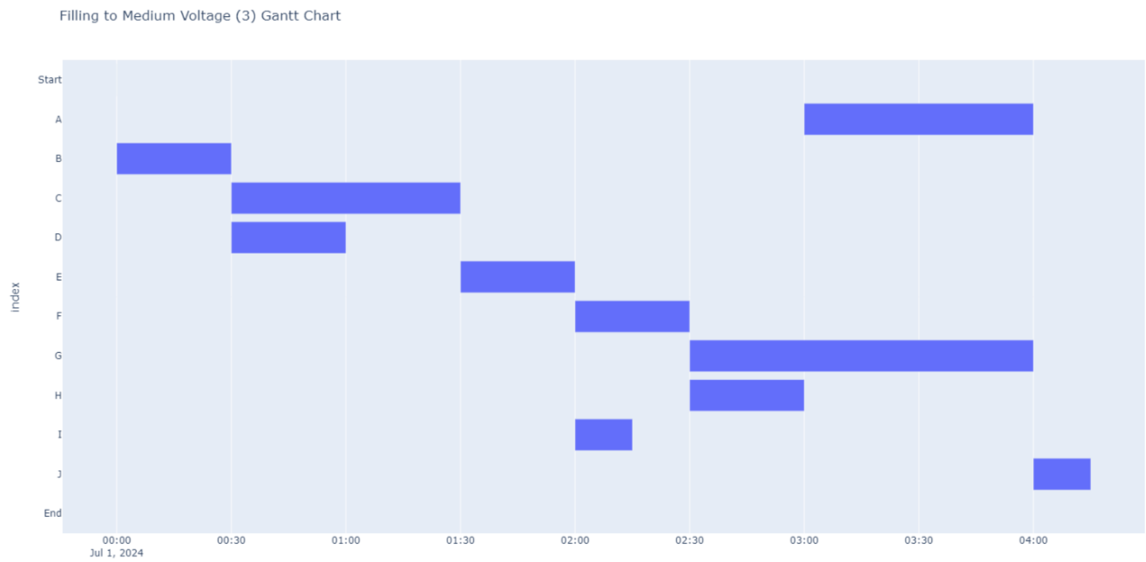
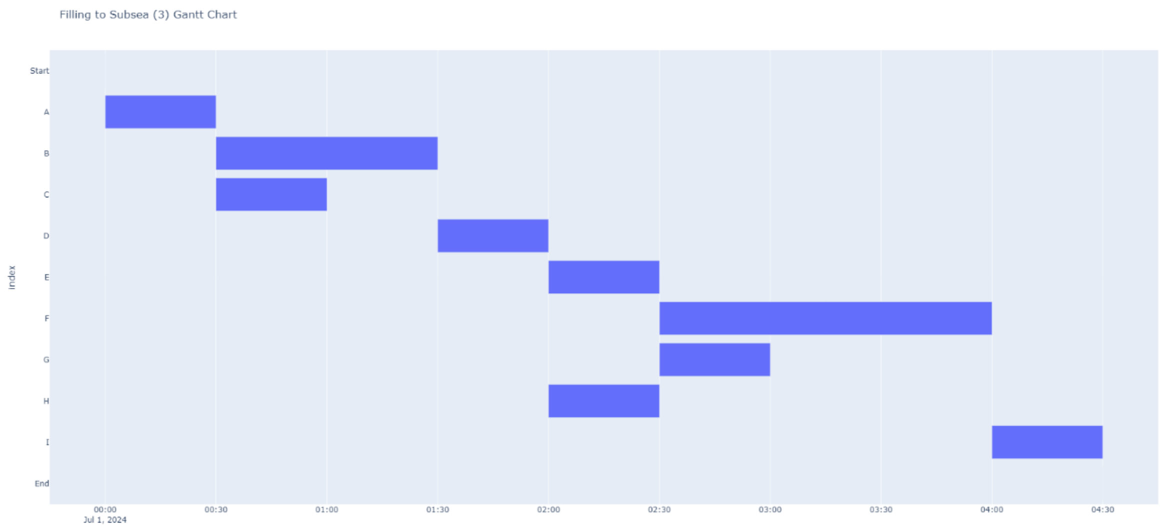
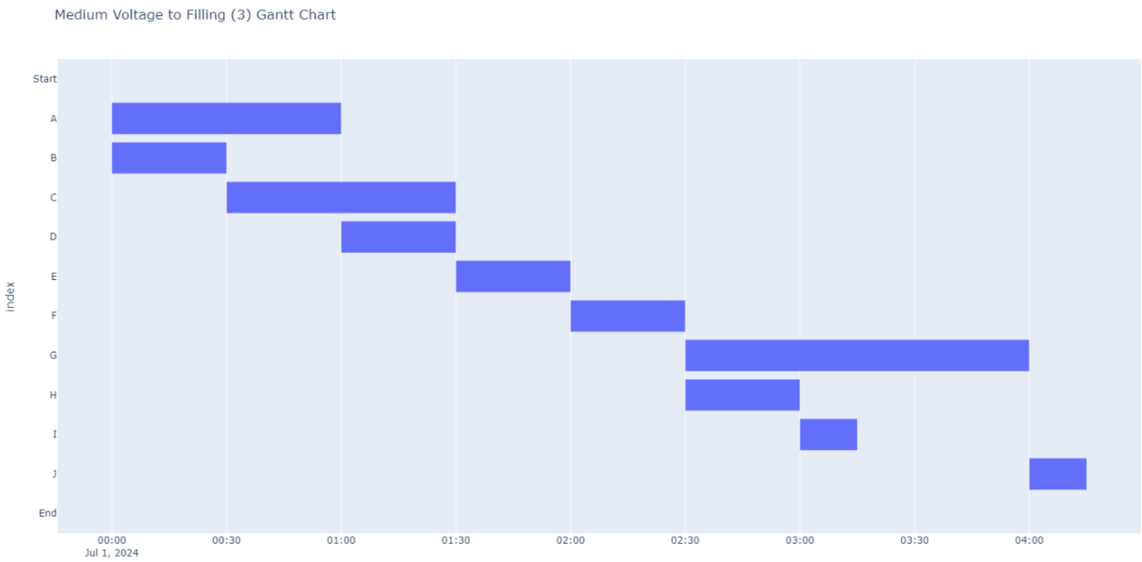


D.2 Gantt Charts 3 operators






Medium Voltage to Filling (3) Gantt Chart
Index
Start
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End
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Jul 1, 2024
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01:00
01:30
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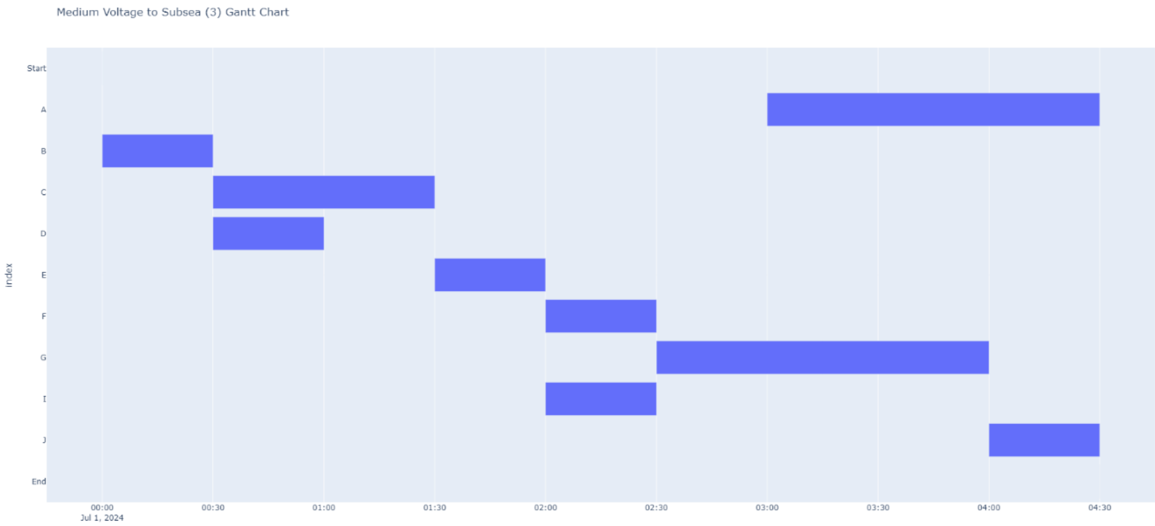
Medium Voltage to Subsea (3) Gantt Chart
Index
Start
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E
F
G
I
J
End
00:00
Jul 1, 2024
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02:00
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04:00
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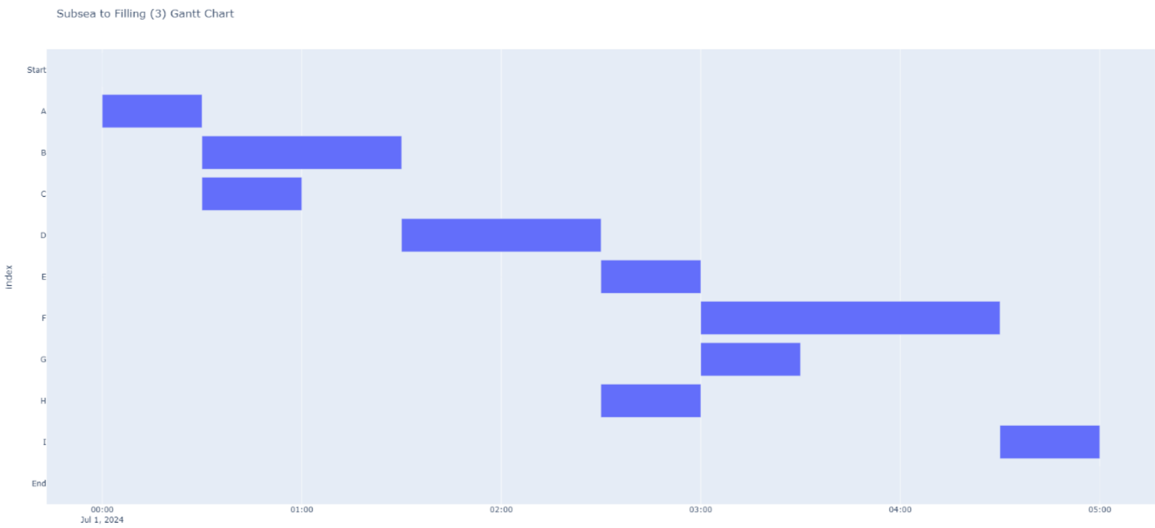
Subsea to Filling (3) Gantt Chart
Index
Start
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I
End
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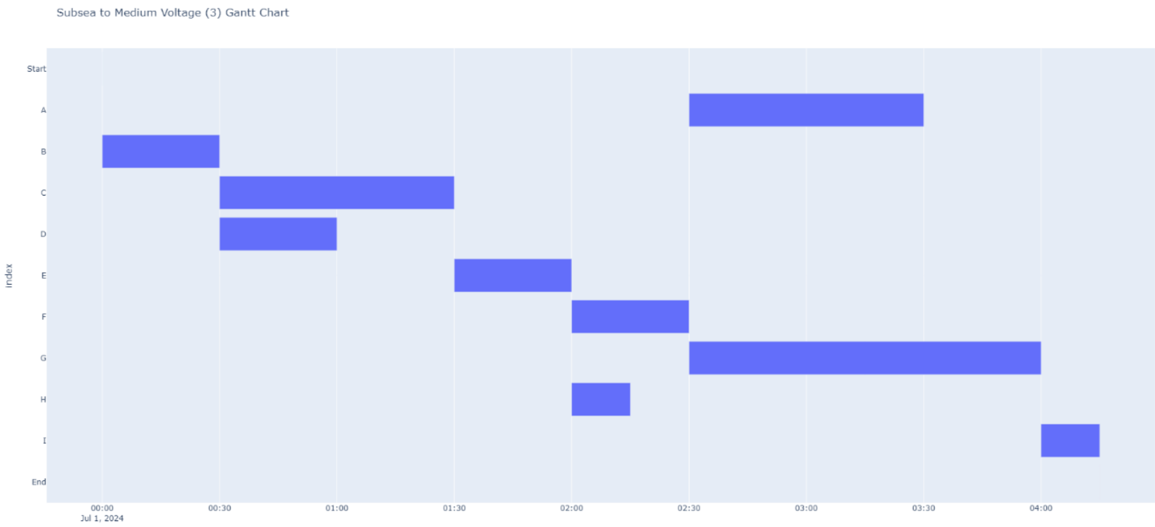
Jul 1, 2024
01:00
02:00
03:00
04:00
05:00



Subsea to Medium Voltage (3) Gantt Chart
Index
Start
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B
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D
E
F
G
H
I
End
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Jul 1, 2024
00:30
01:00
01:30
02:00
02:30
03:00
03:30
04:00

Appendix E Interview

Interview
Changeover Process Jacketing Line 2

For TKF, I have been researching the changeover process for Jacketing Line 2 for the last six months. During that process, I consulted with a number of you about what the current process entails and where the pain points are. I used that feedback to develop a new schedule so that the process could be carried out faster.

To evaluate this schedule, I would like to conduct another interview in which the current process is compared to the new process. For this, I need your input. This interview will start with a questionnaire after the introduction to evaluate the current process. After this questionnaire, the new process is explained, in which the expected adjustments and the duration of the process are discussed. After that, the questionnaire of the first process is asked again to be able to compare the expectations about the new process with the old process.

By answering these questions, you agree that your answers will be used for the research. These answers cannot be traced back to the person in the research and will not affect your work.

Current process

First I will give an example of a current process to see how it is carried out now, in reality, there can be small changes per person. But this is the basis that has been used for how the process is carried out in general. This example is in English, provided there is something in it that is not clear, you can find all these activities in Engage.

In this case, the current changeover process of jacketing from subsea to medium voltage jacketing can be seen as an example. For this questionnaire, all processes that can be carried out must be taken into account. This involves the changeover between the production of subsea filling, subsea jacketing and medium voltage jacketing

Time line JA2 Subsea to Medium Voltage

Process / **When the process is perfomed during rebuild**

Where	Type	Process	Number of people	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Line	Previous process	Putting away cable from previous production	2	x	x	x	x												
	Startingpoint	Remove Highway from line and put it away	2					x											
	Endpoint	Remove Highway from line and put it away	2						x										
	Cleaning	Drain hopper and put material away	1							x									
		Rinse with PVC	1							x									
		Remove and clean Qu200 head	1								x	x							
		Pull and clean 'worm'	1										x						
	Set up	Put 'worm' back	1										x						
		Place and attach Qu100 head	1											x					
		Place the correct spray attachment	1												x				
		Put right material at line	1													x			
		Turn on the heating of extruder	1													x	x	x	
		Set up inkjet printer	1															x	

Extra processes	Name		0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Time between	Break		x															

Current Process Questionnaire

These questions will be answered by means of a likert scale, this scale has 5 possible answers in this study. The answers can be entered in the answer table below the questions.

Very dissatisfied **Dissatisfied** **Neutral** **Satisfied** **Very satisfied**

1. What is your opinion on the feasibility of the current process?

2. How satisfied are you with the clarity of the activities in the current process?

3. How satisfied are you with the duration of the current process?

4. How satisfied are you with the number of operators with whom the process is carried out?

5. How satisfied are you with the order in which the process is executed?

6. How satisfied are you with the effectiveness of the current process to complete the work?

Select 1 answer per question by putting an x in it

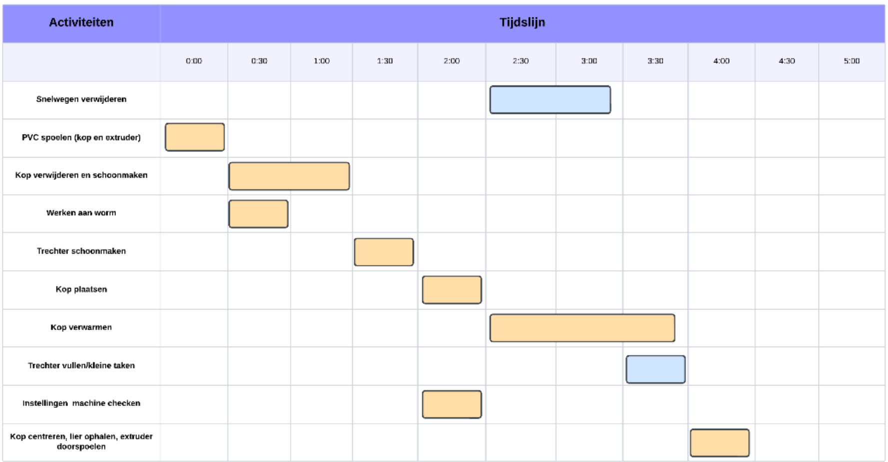
Answer					
Question	**Very dissatisfied**	**Dissatisfied**	**Neutral**	**Satisfied**	**Very satisfied**
1					
2					
3					
4					
5					
6					

New Process

For the current process, calculations have been made with the help of input from the employees to find new schedules that are theoretically optimal. For this purpose, the duration of the current process has been taken for each activity. For each activity, the minimum number of operators is included so that none of the activities are planned if they cannot be carried out due to a shortage of operators. The calculations with the schedules take into account the priority between the different activities to ensure that no activities are planned that cannot yet be carried out.

Below you can see 1 example of a diagram that came out of the calculations. This is the same process as seen earlier for the current process. For this scheme, the activities with 1 operator are colored yellow and the activities with 2 operators are colored blue.

Jacketing subsea naar middenspanning 3 operators



For this process, the most important caveat is that it is carried out with 3 operators. The calculations with the activities show that certain activities can be carried out at the same time. This includes the removal of the highways, this is currently being done first but by combining this with the time the head is on for heating, operators are available at the beginning of the process. These operators can then carry out the first activities at the head so that it is completed at the same time. In addition, it is important to carry out the final preparations when someone is already working on the last head activities and when the head is being heated. In this way, production can be started as soon as possible after heating up.

From the different schedules for all the different changeover processes came new times that the processes take to be carried out. These were compared with the current times to carry out the processes and from that came an improvement in time for each process.

Process	**Current time (Hr)**	**Model Time (Hr)**	**Improvement**
Fill to MV	6.5	4.5	-31%
Fill to Subsea	6.5	4.5	-31%
MV to Fill	7.5	4.25	-43%
MV to Subsea	6.5	4.5	-31%
Subsea to Fill	9.5	5	-47%
Subsea to MV	7.5	4.5	-40%

New Process Questionnaire

These questions will be answered using a Likert scale, this scale has 5 possible answers in this study.

Very dissatisfied **Dissatisfied** **Neutral** **Satisfied** **Very satisfied**

1. What is your opinion on the feasibility of the new process?
2. How satisfied are you with the clarity of the activities in the new process?
3. How satisfied are you with the duration of the new process?
4. How satisfied are you with the number of operators with whom the process is carried out?
5. How satisfied are you with the order in which the process is executed?
6. How satisfied would you be with the effectiveness of a new process to complete the work?

Select 1 answer per question by putting an x in the box

Answer					
Question	**Very dissatisfied**	**Dissatisfied**	**Neutral**	**Satisfied**	**Very satisfied**
1					
2					
3					
4					
5					
6					