INCREASING THE THROUGHPUT
FOR INSULATING AND DEGASSING MEDIUM VOLTAGE CABLES

Bachelor thesis

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Foreword

This is my thesis on 'increasing the throughput for insulating and degassing medium voltage cables'. The subject for this research was Twentsche Kabelfabriek BV in Haaksbergen, who also gave me the time and space to conduct it on-site. The research is done to put my knowledge into practice and to conclude my bachelor study, Industrial Engineering and Management, at the University of Twente. The reason for TKF for having this research was to get a fresh look at their production processes and to find a way to increase the throughput. I started in late January and finished in July, after which I had some more time to finalize this report and discuss its results until September.

Supervision from TKF came from Henk Jan Horstink and Tom Bijen, supply chain manager and capacity planner at the Energie department, respectively. I would like to thank them for their guidance this whole research, which was something I wished for at the beginning. It really helped me to get a grip on what I was doing, i.e. what next steps to take or what direction to head for. Together they carried the feeling that they supported this research, which was a great motivator. To have their supervision and assurance that this research would succeed, I am very grateful.

I also want to thank my supervisors from the University of Twente. Petra Hoffmann guided me during the set-up and the research itself, and knew how to motivate me and be critical to my own work. Later on, Eduardo Lalla-Ruiz was there to guide me in the technical parts and was more of a helping hand than a standard second supervisor normally is.

Tom Boerrigter,

Enschede, September 2019

Summary

In this research we find an answer to the question how to increase the throughput at insulating and degassing medium voltage cables. The setting of this research is Twentsche Kabelfabriek (TKF) location Haaksbergen, department ‘Energie’. In an assessment of the ongoing problems in their production line, we encounter the core problem that states that short-term decisions do not take the whole production line into account. Because the whole production line is quite complex, we narrow our scope to the insulating and degassing stages.

We describe the production line within our scope with relevance to our KPIs. These KPIs are throughput, lateness in delivery and standstill of degassing rooms. For measuring these KPIs, we want to have a framework accompanied by a solving method. Of course, there are multiple frameworks and solving methods, and we have to choose the one that fits our situation best. This is done by a review of regularly used frameworks. When comparing, we found that creating a custom algorithm to our situation suits best, and a heuristic must be applied to solve it. For this, we chose steepest hill climbing. Both the custom algorithm and the heuristic are written in Visual Basic for Applications, because of TKF’s familiarity with Excel and VBA.

We have created an Excel tool that retrieves data from the database of TKF and creates a production schedule. Based on the intentions of the user, both the conceptual schedule and the schedule created by steepest hill climbing can be obtained independently of each other. The tool has to purpose to be easy to use and has several options to specify the situation. This tool is also the basis on which we have retrieved our results and conducted our experiments.

For the results, we have created three different situations. First, we used the standard situation, after which we conducted two experiments with the following conditions: 1. No standstill of degassing rooms allowed, 2. First two orders are locked. The data for these situations were retrieved at 8 different points in time.

Throughput can be improved significantly by applying the steepest hill climbing heuristic. On average a positive change up to 21,8% was retrieved in the standard situation. Experiments resulted in a lower throughput, but all showed improvement. The lateness in delivery showed us that initially sometimes half of the product are expected to be delivered too late. Steepest hill climbing and the experiments did not really change these numbers. Standstill of degassing rooms were highest when applying steepest hill climbing, which gives the impression that a higher use of the degassing rooms does not always result in a higher throughput.

We advise TKF to apply steepest hill climbing with the first two orders locked to create a production schedule. Further, additional research can be done to approach a more continuous schedule which leads to a more realistic expectation.

Definitions and abbreviations

CDCC	Completely Dry Cured and Cooled Curing
Degassing	A process that is used for the vulcanization (form a net) of thick cables with XLPE insulation.
Insulating	The application of three layers of insulating material around an aluminum or copper core by the CDCC line
KPI	Key Performance Indicator
LP	Linear Programming
Production line	A sequence of machines that each contribute an operation for creating the final product
Query	Order to the database to perform a certain action and possibly return information
TKF	Twentsche Kabelfabriek
TKH	Twentsche Kabel Holding
VBA	Visual Basic for Applications

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1 Introduction

This chapter serves as an introduction to the research and its foundations. Section 1.1 and 1.2 give a description of the company and department respectively, where the research was conducted. From section 1.3 to 1.6, we discuss the ongoing problems and provide reasoning for the tackling of our chosen core problem. After choosing our core problem we set a scope for the research (1.7) to which we adapt our research questions and our research design in sections 1.8 and 1.9.

1.1 Twentsche Kabelfabriek BV

Twentsche Kabelfabriek is a producer of electricity and fiberglass cables. It is founded in Haaksbergen in 1930 and has stayed there ever since. In 1980 it became part of the Twentsche Kabel Holding Group which is listed at the Euronext exchange in Amsterdam and became part of the AMX Index. The core business of TKF is creating safe and reliable energy- and data connections with a broad portfolio on cables, systems and services. Their markets can be divided into three segments: Building Solutions (Construction, Rail infra, Sustainable energy, etc.), Industrial Solutions (Heavy industry, Marine & Offshore, Oil gas & Petrochemistry) and Telecom Solutions (Telecom). Besides the factory in Haaksbergen, there is a separate factory in Lochem which produces for Haaksbergen. At this time the location in Haaksbergen has over 480 employees and an office and factory space of 165.000 m2. The location in Lochem is a lot smaller and has only a few dozen employees.

1.2 ‘Energie’ department

The ‘Energie’ department is the oldest and the most complex department at TKF. Its complexity is due to the number of steps the whole process takes. Also, the machines and materials are large and take time to adjust and clean. In Figure 1 an overview of the stages medium voltage cables need to pass in production is given. We will now discuss this overview for a basic understanding of the subjects that are used throughout the whole research.

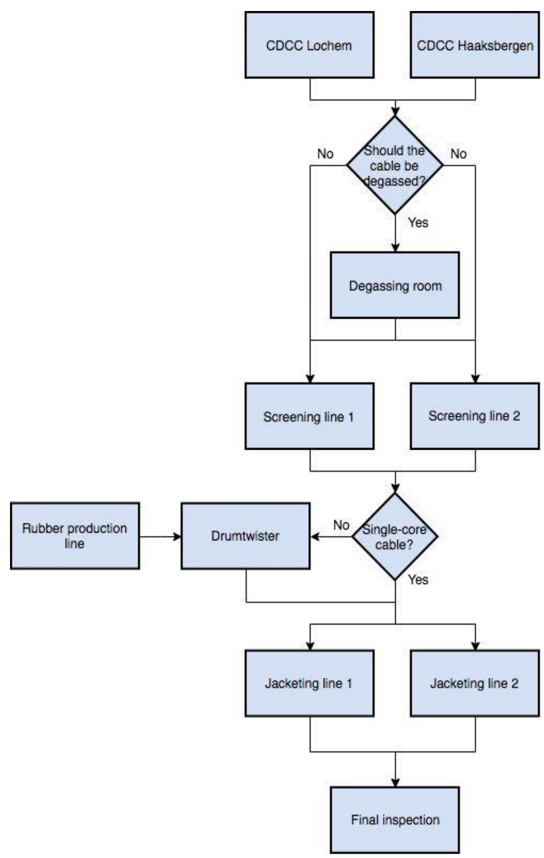

Figure 1: Overview of the production line

The ‘CDCC Lochem’ and ‘CDCC Haaksbergen’ are machines that are located in Lochem and Haaksbergen respectively. These machines cover the core conductor, mostly aluminum or copper, with three insulation layers. When materials produced in Lochem are finished, they need transportation to Haaksbergen. After insulating, the cables enter the degassing process. This process gives the gasses that are released during the heating and cooling of insulation material a chance to escape. If cables are sufficiently degassed they enter the screening line. At the screening line, cables get wrapped with copper wires and tape to ground them. If the end product must be a single-core cable, it can be moved to the jacketing line. Should the cable be a triple-core cable, it first has to pass the drumtwister. This machine places semi-finished products made out of rubber between the cables to fill up the gaps, and then wraps around copper and tape like the screening line. All cables pass the jacketing line for a plastic layer with an injected brand for recognition. The cable has reached its end product state and only needs a final inspection before it can be shipped to the customer.

1.3 Reason for research

A production line such as described can have a lot of differences in throughput times between machines. Different throughput times means there is always a bottleneck present. This bottleneck can of course shift to another machine if speed and occupation are being changed. Balancing out this series of throughput times is not an easy task, and can easily be distorted by a lot of factors whose description can be found at section 1.4. If a distortion at a single machine is not intercepted well, it can influence performances in the whole chain.

At TKF productivity of production is monitored each day, in order to be able to quickly intervene and make modifications to the production planning if necessary. Productivity is expressed as man efficiency and has a calculated target of 85% each day for the whole year. This target (norm) indicates that of all the hours of labour, 85% has to be used at a machine that is in production. Reality turns out that this target is most of the times not met and that productivity heavily fluctuates per day. Together with the management, we conclude that machines and personnel are not used up to standard. To find out possible causes for this action problem, all problems relevant to this case are discussed in the next section.

1.4 Overview of problems at TKF

It is essential for solving an action problem to map all the underlying problems. To get a first good look at the ongoing problems, interviews with various employees with a managerial function were held. Persons were chosen with relevance to planning, production and factory personnel. The interviews addressed the problems within the department concerning the production line and views on the functioning of other personnel in that department. It would be unwise to assume that all relevant problems lie within these two subjects, so we addressed overlapping subjects to catch possible hidden problems by not necessarily sticking to the primal conversation topic.

1.4.1 Number of man-hours cannot be met

Productivity at producing medium voltage cables is expressed as the percentage of realized man-hours spent on production. These hours spent on production are defined as the sum of the processing time and the setting time of a machine. Each year a target is being set and currently 85% of the planned man-hours should be spent on production. The remaining part can be devoted to educating personnel, repair of machines, final inspections or setting up the workspace. If these tasks take up more than 15%, they become a problem. This is rarely the case, especially because educating personnel is something that can be shifted. Unfortunately, there is also an unexplained part that takes up man-hours, which is causing not meeting the target.

Data is recorded at the main database for each machine in the production line. Processing time and setting time are part of these recordings. It is the case on almost a daily basis that the recorded machine-hours do not match the planned man-hours for production. The difference is a loss of man-hours, which is unwanted. Table 1 gives an insight into the loss of man-hours on recent 'normal weeks'. Appendix A: Overview of lost hours week 5, 2019 gives an insight into how the hours lost are monitored on a daily basis.

	Week 2, 2019	**Week 3, 2019**	**Week 5, 2019**	**Week 6, 2019**
Total man-hours realized	2139	2258	2196	2014
Total man-hours lost	361	389	448	378
Percentage lost/realized x 100%	16,88%	17,23%	20,40%	18,77%

Table 1: Total of realized and lost man-hours. (Database TKF, January - February 2019)

Over these 4 weeks in Table 1, 18,31% of the realized hours are lost on average. This means that the same percentage is wasted financially to wages, and it means a delay for the production planning. A delay in the production planning leads to less flexibility in choosing what to produce, which can cause the management to take production decisions that differ from their planning and cause a more negative outcome.

There are multiple reasons for the lost man-hours and they are all addressed in the subsections below.

1.4.2 Lack of motivation operating personnel

Motivation is hard to express, but it is not hard to get a general feeling of the working atmosphere and the corresponding motivation of the operating personnel. From conversations with the team manager and Value Stream Manager, we can say that production work at TKF can be monotonous and not challenging. It can occur that certain personnel does not pick up new tasks without any good reason. It means that they are literally doing their time. This is noticed by their team leader who monitors their performance and attitude. The lack of motivation affects the effectiveness of the personnel negatively, and subsequently production.

1.4.3 Lack of communication about tasks

To continue on the previous problem of the lack of motivation, picking up tasks can go wrong from two sides. Motivation on the one hand, not having control over personnel on the other hand. If a team leader forgets to communicate about future tasks or does not notice someone that is waiting for a new task, time can go to waste. This problem was noticed by the Value Stream Manager. We will not quantify this problem, because of its small impact on the action problem based on the low occurrence frequency. Besides the relevance, it is not the topic of this research to monitor and adjust someone's work attitude.

1.4.4 Production can stagnate

The stagnation of production means that reality deviates from the planning. This results in the problems that are mentioned in subsections 1.4.1.

The stagnation of production is a collective term for a couple of problems that are present at TKF. Because all machines are in a chain, problems at one machine can work on multiple machines or even get enlarged. The problems that fall under the stagnation of production are listed in subsections 1.4.5 to 1.4.10.

1.4.5 Machines can stand still

Every operator on a machine has the task to keep up registration of his hours during their shift. Most of the time these hours are spent on production and conversion, but can also be spent on other tasks that are described as lost hours. During the lost hours, machines can lose its speed or stand still. TKF describes reasons for this as follows:

Code	Description
1	Speed loss
2	Reel change
3	Malfunction machine
4	Production process disruption
5	Error handling
6	Incomplete order
7	Diverse

For code 4 and 7, an added explanation for why this has happened is required to give the team manager an insight. According to the team manager, handling of this registration form by the operators is not done neatly most of the times. Often the explanation is told during the morning monitoring, or is passed from mouth to mouth.

Unfortunately, results are not being recorded for longer than a week. There is no data about what codes for lost hours occur more often than others. To collect this data we would need more time than this research can cover.

The team leader of the factory personnel described that the reason 'Diverse' is most of the times a reel arriving too late. For a description of this problem see section 'Delay by reels arriving too late'.

1.4.6 Degassing room can be full

All medium voltage cables that come out of the CDCC are emitting gas that arises from the heating process at the CDCC. This gas must evaporate before a new layer can be applied to the cables or else it affects the quality. When the temperature is higher, degassing will take shorter. If a reel comes of the CDCC it immediately begins to degas. Setting the reel aside at an empty space in the factory is a way to degas the cable. Another way to degas the cable is to store it in a degassing room. This room will heat up to 70 °C to speed up the process.

TKF Haaksbergen has a small and large degassing room, with space for 4 and 10 reels respectively. For degassing they use Table 2: Degassing times per voltage class as a guideline. This table shows the degassing time in the factory (20 °C) and in the degassing room (70 °C) per voltage class. Each voltage class has its own thickness of insulation.

Voltage class (kV)	Degassing time CDCC cores Insulation thickness (mm)	$Tnom_{20}$ 20 °C [h]	$Tnom_{70}$ 70 °C [h]
6/10	3,4	87	52
8,7/15	4,5	120	55
12/20	5,5	160	59
18/30	8	300	73
≥20/35	10	470	89

Table 2: Degassing times per voltage class. (TKF, 2019)

As can be seen from the table, degassing in a degassing room can be $\frac{87}{52} = 1{,}67$ (3,4 mm insulation) up to $\frac{470}{89} = 5{,}28$ (10 mm insulation) times shorter than in the factory. This can save a relevant amount of time and gives more flexibility to the production process. On the other hand, the degassing room can be a bottleneck and slow a certain order down because of the lack of space, which causes the reels to degas outside the degassing room. This is the main problem that is experienced.

To sketch an example: On average, a cable has to be in the room for $\frac{52+55+59+73+89}{5} = 2{,}73$ days. In reality, cables of higher voltage classes get priority because this saves the most time. For now we take an even distribution of voltage classes for convenience, because it saves a lot of calculations. This average already sketches the problem and will be amplified in reality because of priority to higher voltage classes. According to the log data from the first month of production in 2019, ranging from the 3rd of January till the 3rd of February, 194 reels of cables are produced. On average this is 6,26 per day. Multiplying this by the 2,73 results in 17 reels. To conclude: in 2,73 days 14 reels can be degassed, while 17 reels are produced. This applies for an even distribution of voltage classes, meaning that in reality degassing rooms are longer occupied than 2,73 days because of the aforementioned priority to higher voltage classes.

To finish the degassing process, cables that come out of the degassing room need to cool down. Cooling down can take half a day up to a whole day. It is mere guesswork when a full reel has cooled down enough, and depends on when the factory worker finds it sufficient.

1.4.7 Delay by reels arriving too late

At the ‘Energie’ department there is always one person working on a forklift truck. This person lifts heavy reels to the place where they are needed. Most of the times he works on call and can experience a high workload from time to time. There are large carts on which factory personnel can move reels themselves, but these are taking up much space. This is why they do not get used all the time. To have an extra forklift truck is quite expensive, this is why TKF chooses to have only one.

There is no overview on where reels are, this means that a shortage can occur at multiple places at the same time without someone noticing. Should a reel be needed at a machine, the operator calls the forklift truck driver. If he gets called a lot because of the multiple shortages, the workload gets too high and factory personnel has to wait until their reel arrives. This causes the process to slow down or the machine to stand still.

1.4.8 Not enough semi-finished products on stock

Semi-finished products are needed to fill up the spaces between cores in a triple-core cable, and are made out of rubber. The decision point of making a single core or a triple-core cable can change between two points in the chain. The first point being at the CDCC, which means that the demand at the rubber production line is known a couple of days beforehand. The second point is located just after the screening line and gives the rubber production line no time to anticipate. Choices at this point are mostly made out of necessity and can have the result of having an empty stock. This means that rubber needs to be produced which can have its effects on the production schedule.

1.4.9 Machines cannot handle the demand

As a result of the congestions and gaps, a queue can grow at a machine. The speed of the machine depends on the thickness of the insulation, but is also fixed per thickness. In almost all cases, there is always a machine that produces the slowest. This machine is at that moment the bottleneck and must be kept going at all cost.

1.4.10 Short-term production decisions do not take the whole production line into account

Short-term decisions are the decisions that regard the products that are currently in production or ready for production. They are made by the production planner, who has the best view on what is to be produced and what is already in production. Currently and over the past years, the production planner made his short-term decisions based on experience. There is no set of rules or calculations involved. With experience one can come a nice way, but it is insufficient on a production line of this scale. The longer the series of different machines, the more complex it becomes to calculate the effects a short-term decision has on all machines. There is no way that the production planner has a detailed overview of the current state of the production line, and where its bottleneck is positioned. A short-term decision that may seem proper if you look one step ahead, can be counteracting at another step further down the production line. This results in congestions and gaps in the production line. It is reported by managers we spoke with that this often occurs. There is simply no tool available to take the whole production line into account.

1.5 Problem cluster

The problems that are present at TKF are connected to each other. They can all be described as causes for the action problem. Figure 2 displays the action problem in bold at the right. The problems with an outgoing arrow are causes for the problems they are pointing to. From what we can see, there is a loop present that can cause a downward spiral.

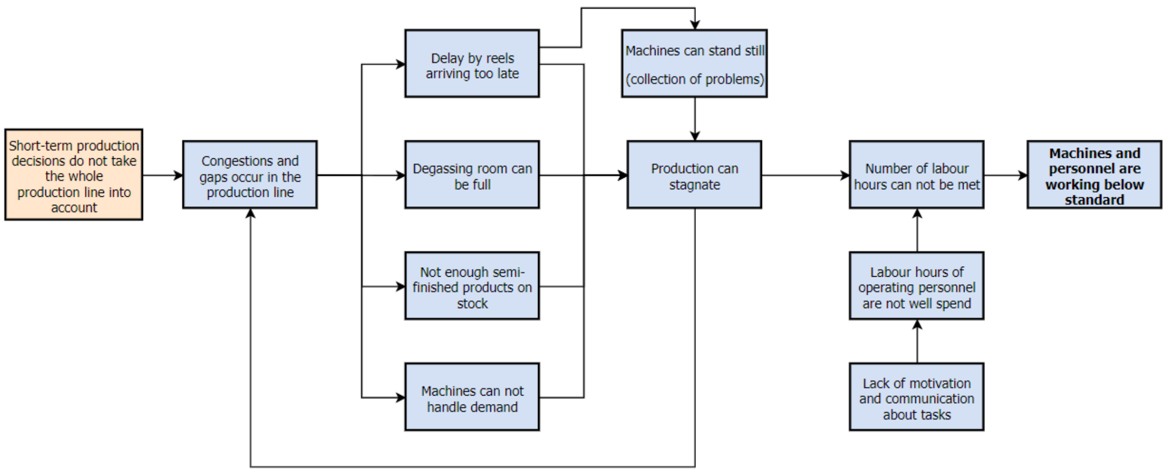

Figure 2: Problem cluster

1.6 Core problem

As it can be seen in the problem cluster, there are multiple problems going on at TKF. It is clear that we want to get as many problems out of the way as possible. Therefore we need to look at the effectiveness of solving a particular problem. If we solve a problem, but not the cause, it is most likely that the problem is going to occur again after some time. It is clear that we need to tackle a problem that has no cause. (Heerkens & Van Winden, 2012) describes a set of rules to find this core problem, the four rules of thumb.

First of all, the problem needs to be present. If there is no evidence that it really is a problem, then it has no use to tackle it. We have covered the presence of the problems in section 1.5.

Second, we need to go back to the problems that have no causes themselves. In our problem cluster, there are three problems that are possible core problems: 'Machines can stand still', 'Short-term production decisions do not intercept congestion and gaps' and 'Lack of motivation and communication about tasks'.

Third, problems that cannot be influenced are no core problems. The standstill of machines has multiple causes that all are hardly influenceable. It has to do with the skills of the operating personnel, and the reliability of the machines. The causes are all out of the scope of this research and thus not to be influenced.

Fourth and last, choose the most important problem which is the problem that has the most result. In this case, it is the problem 'Short-term production decisions do not intercept congestion and gaps'. It is connected to 7 other problems and has an effect on the loop. From now on, this is our core problem that is going to be tackled in this research.

1.7 Setting the scope

With the use of the problem cluster we have found our core problem and in doing so made boundaries that prevent us from deviating into the wrong direction. But, even with having to deal with one problem, researches can vary over the same problem when there is difference in the scope. We set our scope by taking into account our limitations and TKF's demands for the research to be of value for them.

1.7.1 Limitations

For the execution of this research, we have a directive of 10 weeks. This has its effects on, for example, the complexity of the theory, the number of factors that can be dealt with and what shape experiments can be molded in.

Evaluating the number of variables of the whole production line gives us a first insight into its complexity. According to the capacity planner and supply chain manager, there are over 100 products to consider. Each product has its own specifications like setup time or thickness, and production length varying per order. For all of the 10 machines that can be used to produce the cables, regulations are never the same. Operating times differ, product priorities can shift because of the situation and exceptions are not unfamiliar.

For our research we preferably want a single theory to be sufficient for finding solutions, because of the time it takes for finding, understanding, evaluating the theory and translating it to our situation. At the 'Energie' department we have machines in series and in parallel, thus needing different theoretical approaches. With the addition of the many variables, it can be predicted that most theories do not cover all factors which could lead to the necessity of combining different theories.

1.7.2 Scope

Due to the arguments in section 1.7.1 we need to narrow down our scope for it to fit in the stated 10 weeks. With the agreement of TKF that we cannot take all machines of the production line into account, we selected those that have the most room for improvement and can have a large effect on the problem. This is presented in Figure 3.

The CDCC and degassing rooms are the parts in the production line where most of the production order is determined. Because there are a lot of combinations of products in different orders, it is impracticable to calculate these by hand. This is also the reason why there is room for improvement because there has never been insight in the effects of decisions at this stage. For the subsequent stages in the production line, the production order is mostly locked and its effect is easier to predict manually.

With our new scope, we cover just a few machines and stages. This means that our variables are fewer in number and we expect not to need a combination of theories. Also, computing time is drastically lower when obtaining results.

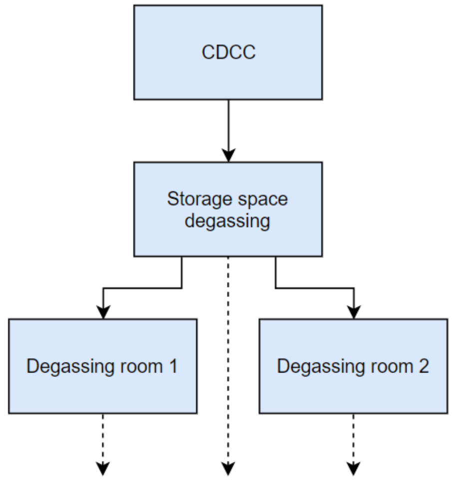

Figure 3: Overview stages of scope

1.7.3 Key performance indicators

We want to measure our core problem with the help of key performance indicators (KPIs). The KPIs are drafted variables to analyze the outcomes in the result phase of this research. They are a result from TKF's wishes and knowledge of the researcher on this topic.

The first KPI is throughput, meaning the rate at which items emerge from the process, i.e. the number of items passing through the process per unit of time (Slack, Brandon-Jones, & Johnston, 2013). A production line that is efficient with its time, can cause a high throughput rate. The more products produced in a time unit, the greater the financial benefit.

Lateness in delivery is our second KPI. With the customers of TKF, a delivery date for each end product is set before production. It can be seen as a deadline that in some cases cannot be met, due to several reasons like machine or production failure. This KPI let us see if the current production and our research results operate within the prefixed boundaries.

Standstill of degassing rooms is our third and last KPI. By standstill, we mean that a degassing room is not degassing any reels and is not cooling down nor warming up. It simply means that the degassing room has no temporary function, which can raise the question if both degassing rooms are still necessary or if it is not used to its full extent.

1.8 Research questions

We distinguish research question between one main question and multiple sub-questions. The sub-questions serve as smaller steps to provide an answer for the main question, which is going to be answered at the end of this research.

1.8.1 Main question

In order to raise the efficiency of the use of machine and personnel in the production line, we want to establish a high and constant throughput by answering the following question:

“How can TKF gain a higher throughput of medium voltage cables at the insulating and degassing stages?

1.8.2 Sub-questions

1. **What are the key aspects of the production line that are relevant to the KPIs?**

We want to describe all of the properties of the production line that lie within our scope. This is necessary for getting to know the situation and correctly translating it for later optimization purposes.

2. **What framework must be used to express the production line for optimization purposes?**

In order to translate our situation, we must have the tools for expressing it. We need to choose the framework that suits the most to our situation.

3. **What method must be used for optimization calculations?**

Besides a framework for expressing our situation, a method is needed to quantify the situation.

4. **How to implement TKF's situation into the framework and method?**

Because there are lots of ways to translate the same situation, a wrong turn can easily be made. We want to create a translation that is organized, user-friendly and is low in computing time.

5. **What are the effects of different production approaches?**

When having the tools to calculate the current but also a custom situation, we can observe the effects of specific conditions being changed and if that might be beneficial.

6. **How to implement and maintain the production approaches and their outcomes?**

It is necessary to build a guideline that ensures the same results in the future and preserve the value of this research.

1.9 Research design

This research is built up in 7 chapters, each with its own purposes to answer a sub-question.

Chapter 1 is about problem identification and has this research design as its result.

Chapter 2 serves as a context analysis, which serves to provide answer for research question 1. Information for this comes from TKF and every detail that is analyzed can be a building brick for a more correct conclusion at the end of this research.

Chapter 3 contains a review of different frameworks and methods, that all have its own properties for expressing and calculating similar situations. When reviewing, we choose the ones that are closest to our objective and need little modifications. Logically, in this chapter we provide answer for sub-questions 2 and 3.

Chapter 4 describes the implementation of our framework and method to resemble the situation of TKF. Research question 4 is answered here, and we will have a model for quantifying situations.

Chapter 5 encompasses all results that come from current situation simulations and the experiments that lie within the possibilities of TKF. It is the answer to our 5th sub-question.

For maintaining the presented results in the future, we provide the user a guideline in chapter 6. This guideline encompasses the fixed and unfixed parts of the tool and describes the steps to execute the experiments.

To finalize our research, we describe our conclusions, discussion and recommendations in chapter 7.

2 Key aspects of the production line

In this chapter we discuss the processes and its accompanying numbers and rules that are of importance to our production line. We can utilize these as a basis for the findings in chapter 4. Section 2.1 describes the processes that precede to insulating and degassing. Subsequently, we discuss insulating and degassing in sections 2.2 and 2.3 respectively. To close our chapter, we describe our expression on the remainder of the production line in 2.4.

2.1 Production planning

Before production can be started at the CDCC, a couple of steps are preceded. For instance, the material that is used for production must be available, and a plan is needed for creating a production schedule.

2.1.1 Order release

Orders at the ‘Energie’ department are received from the production planning department. They have contact with the customer and agree on a certain delivery date. It is up to the ‘Energie’ department to produce these products, and ideally produce them on time. From an overview with the open orders, which is an overview that could even go up to half a year from now, orders can be selected to produce. By releasing them, a priority is given and they are in the waiting line ready to be produced. This is then linked to the operating employees.

2.1.2 Wire drawing

Wire drawing is the production step that precedes insulation. Wires come in the form of aluminum or copper and are drawn by a machine designed for this material. The wires are bundled in bunches and transported on increasingly faster-turning discs, which causes the material to stretch. Dies for drawing with synthetic diamonds give the aluminum wire a controlled diameter. The produced wire is rolled on a reel and is ready for insulating.

Because the wire drawing precedes the insulation, one cannot start insulating without having thought about this step. The schedule for insulating must always take into account the schedule of wire drawing.

2.1.3 Expression summary production planning

Expression	**Answer**
The connection between wire drawing and insulating	The wire first has to be drawn for it to be insulated. Schedules need tuning.
Order release	An order can be produced if it is release by the management.

Table 3: Expression summary production planning

The expressions in Table 3 define the boundaries that we need to take care of when obtaining the current schedule.

2.2 Insulating

The CDCC is the most complex insulation line at TKF. CDCC is an abbreviation of Completely Dry Cured and Cooled Curing. In short, the process is as follows: Aluminum or copper conductors are preheated and provided of 3 layers of plastic in 1 spray nozzle by extrusion. Next, the insulation is vulcanized and cooled. This happens in a long trajectory of heated tubes with nitrogen filling, and later by tubes and baths with cooling water. An accumulator system makes it possible to weld a new reel with a conductor to an emptying reel. In this way, production can be continued without interruption. The cables consist of 3 layers of plastic: semiconductor – insulation – semiconductor. The plastics that are fed to the extruder must be extremely pure, meaning there cannot be any dust or residual products present. This is why a thorough clean-up is needed after a material or setup change. Without the use of nitrogen in this process, gas bubbles can arise within the insulation and make the cable useless.

2.2.1 CDCC Haaksbergen and Lochem

TKF possesses 2 CDCC lines, 1 in Haaksbergen and 1 in Lochem. The CDCC in Lochem is bought for expansion of the production line in Haaksbergen. Besides medium voltage cables, it can also produce high voltage cables. Its production speed is a lot higher because it is a newer and more advanced machine. A disadvantage of this machine is that it is located in Lochem and must be transported to Haaksbergen for further operations. When a product is finished it is transported to Haaksbergen the next day, this takes about half an hour. Operating times for the CDCC in Lochem are either 0 hours per week or 80 hours per week.

The decision to produce in Lochem is not an easy decision and depends on the current situation. Because of complexity reasons we consider the CDCC as only 1 machine, namely the CDCC in Haaksbergen. This choice is proposed by TKF and ensures that a solution with this situation still has value for them. Reason for this are the future plans for the CDCC in Lochem (it can produce more than medium voltage cables) and that the majority of the cables are produced in Haaksbergen.

Operating times in Haaksbergen are continuous for the CDCC. There are three work shifts of 8 hours per day that alternate. A workweek starts with the night shift on Sunday at 22:00 and understandably ends there too.

When production is started at the CDCC, the first couple of meters are for testing the setup and usually wasted. The last couple of meters are wasted too, because the machine operates until the order is complete, leaving the residual meters for production support. In between these wasted meters, the machine can keep running until the reels in use are full or empty and need changing.

In the case that a different product must be insulated, the CDCC needs a new setup. Sizes possibly need to be changed or another material is used. The associated setup times are set in the database of TKF and can vary per product.

2.2.2 Expression summary insulating

Expression	Answer
There are 2 CDCC lines. 1 in Haaksbergen and 1 in Lochem	We consider only the CDCC in Haaksbergen
Operating times CDCC Haaksbergen	Continuous. Workweek begins and ends on Sunday at 22:00
Setup time of a product	Is set and can be found in the database

Table 4: Expression summary insulating

2.3 Degassing

Degassing is a process that is used for the vulcanization (form a net) of thick cables with XLPE insulation, and starts directly after the insulation process. XLPE is a type of plastic that is applied to the core of energy cables. Over time, a chemical reaction takes place that makes the insulation capable of enduring a short maximum operating temperature of 200 °C (short-circuit situation). The conventional operating temperature of a cable is at most 90 °C. Each cable degasses automatically and must be completely degassed before the next operation. After a specified time, the structure of the XLPE changes and the cables is cooled down. We describe the two ways by which a cable can be degassed at TKF.

2.3.1 Degassing room 1 and 2

As it is earlier described in sub-section 1.4.6, TKF has 2 degassing rooms available for medium voltage cables. In this research we call these degassing room 1 and degassing room 2, with a respective capacity of 10 and 4 reels. The reels with the insulated cores are placed in a room with heated water tanks by a forklift truck driver.

The rooms are filled based on the decisions of the production planner. Most of the times this depends on the ongoing orders and their longest degassing times. After the room is filled it is closed and cannot be opened in the meantime. It takes about 24 hours for the degassing room to get heated up (70 °C) and cooled down altogether. For the time it takes to degas all the products within the degassing room, we look at the product that has the highest voltage class. The higher the voltage class, the longer the degassing time (see Table 2: Degassing times per voltage class. (TKF, 2019)). The product with the longest degassing time at 70 °C defines the operational time of that degassing room and all the other reels stay in there for the same time. This can also lead to cables with a lower voltage class that are degassed much earlier, but cannot be released from the degassing room because it will not be opened. Cables that have a voltage class of 6/10 kV and lower are never put in a degassing room, because the difference in degassing time is too small.

2.3.2 Storage space degassing

Because TKF does not have the space to put all reels in degassing rooms, they make use of the natural degassing characteristic of the medium voltage cables. In 'Table 2: Degassing times per voltage class. (TKF, 2019)' we can see the degassing times in hours if they are not put in a degassing room (20 °C). The storage space for these reels comprises 15 rows with 4 places in each row. Next to each row there is a pillar on which a paper is placed with information about the reels (voltage class, order number, etc.).

2.3.3 Expression summary degassing

Expression	Answer
Space in degassing room 1 and 2	10 and 4 reels, respectively
Warm-up and cooling-down time together	24 hours
Products excluded from degassing rooms	Voltage class 6/10 kV
What products are placed in a degassing room?	Depends on production order and decisions of production planner
Number of storage places outside degassing rooms	60
Degassing times outside and inside the degassing rooms	Table 2: Degassing times per voltage class. (TKF, 2019)
Operating times degassing rooms and storage space	Continuous. Workweek begins and ends on Sunday at 22:00

Table 5: Expression summary degassing

2.4 Remaining production steps

As we discussed in chapter 1, the production line consists of more steps than just insulating and degassing. 'Table 6: Maximum speed of every production step' shows the maximum speed each machine is capable of. It does not mean that these machines are set to this speed on a normal basis because the speed of a machine depends on the thickness of the cable. The table gives an indication of the production speed proportions.

Production step	Max. meter/minute
CDCC	25 m/min
Screening line 1	125 m/min
Screening line 2	100 m/min
Drumtwister	100 m/min
Rubber line	25 m/min
Jacketing line 1	125 m/min
Jacketing line 2	125 m/min

Table 6: Maximum speed of every production step

The CDCC, together with the rubber line, are the machines that have the lowest maximum production speed. Based on these numbers we can state that these have the potential to be a bottleneck. On an average day, the rubber line does not have to produce constantly because rubber is only needed for producing triple-core cables. This means that there is extra time available most of the times to cover a potential problem and produce rubber if the stock is running empty. The CDCC, on the other hand, is with its lowest maximum speed and continuous production schedule a constant threat to be the bottleneck. When TKF makes use of the CDCC in Lochem, they see it as a last resort so we will not take this machine into account.

For the remaining production steps we conclude that these are no threat to be a bottleneck on an average day, meaning there are no major defects or production fails. What this implies is that we do not have to worry about the connection between the degassing rooms and the rest of the production line. In this research, we consider this part of the production line never saturated. Should there be any disturbing factor for the complete production line, it is up to TKF to draw conclusions and consider the effects.

3 Theoretical framework

In this chapter we are finding the answer to sub-question 2 and 3, “What framework must be used to express the production line for optimization purposes?” and “What method must be used for optimization calculations?”, respectively. In section 3.1 up to 3.4, we discuss frameworks that are compatible with the situation of this research and are widely used. Subsequent to that, we discuss one or multiple solving methods that come with the framework or are applicable to it. To conclude the chapter and to provide an answer for the two sub-questions, we develop a concept matrix to score our findings and substantiate our choice in section 3.5.

Below, we describe 4 different theoretical frameworks. From a literature search in the databases of Scopus and Web of Science, we discovered that these are widely used and have been applied to similar cases. Of course, there are a lot of other theoretical frameworks but they did not pass our first scan on applicability.

3.1 Linear programming

3.1.1 Framework

Although linear programming may sound like it needs coding on a computer, it does not necessarily has something to do with that. It is a method for solving optimization problems and eventually can be made applicable for the use of a computer, to make use of its computing power. According to (Winston, 2004) a linear programming problem is an optimization problem for which we can do the following:

1. We attempt to maximize (or minimize) a linear function of the decision variables. The function that is to be maximized or minimized is called the objective function.
2. The values of the decision variables must satisfy a set of constraints. Each constraint must be a linear equation or linear inequality.
3. A sign restriction is associated with each variable. For any variable x_i, the sign restriction specifies that x_i must be either nonnegative ($x_i \geq 0$) or unrestricted in sign (urs)

An LP problem has an objective function that gives a score on the decisions that are made. This score creates support for optimization. This objective function is linear and built on variables that depend on decision variables, accompanied by accessory parameters. Constraints describe what is possible in a situation, otherwise objective functions for minimization and maximization will always turn out to be 0 and infinity, respectively. These constraints are built from variables and parameters too.

3.1.2 Parallel machine scheduling

On the same thought as linear programming, we have parallel machine scheduling. Parallel machine scheduling theory is the study of constructing schedules of machine processing for a set of jobs in order to ensure the execution of all jobs in the set in a reasonable amount of time (T.C.E. Cheng, 1990). It has the objective to optimize the schedule in such a way that less time is wasted between jobs, given situation-specific constraints and variables. In some situations precedence constraints are added, setup times are taken into account or operating times can be seen as a restriction.

3.1.3 Solving methods

Linear programming problems start off as small problems that can be calculated by hand, but as soon as the number of variables rises or the event horizon moves further away, it quickly is not efficient to calculate these problems without the use of a computer. There are a lot of companies providing a linear programming solver, with Microsoft being the most well-known. Microsoft Office provides a tool in Excel called 'Excel Solver', which makes it easy to translate an objective function, variables and restrictions into a computer and calculates the possible outcomes in order to pick the minimum of maximum.

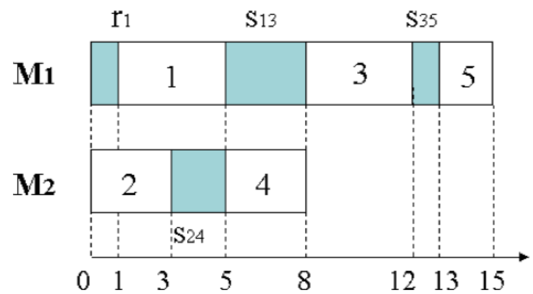

Figure 4: Example of a constructed schedule using parallel machine scheduling. Source: (Gacias, Artigues, & Lopez, 2010)

Parallel machine scheduling is mostly solved by handmade solvers in the software of one's own likes. Still, there are some companies that provide a solver as an add-on from a software package. Because the theory is less used than linear programming, the software is less used and developed, leaving most solvers with missing functions that might be applicable to most situations.

3.2 Custom algorithm

3.2.1 Framework

Algorithms are widely used in multiple disciplines and can be expressed as a set of instructions. In mathematical situations, they are mostly used for computational purposes. The instructions in an algorithm can range from just performing one task, to whole software programs and beyond. The limit of an algorithm depends on the allowable size of the software it is written in.

The instructions that an algorithm perform can be very specific, which makes it adaptable to any situation. This is the reason that a custom algorithm represents a situation much better than a general algorithm. To let the algorithm make decisions, data is needed as an input. When put through the algorithm, the data is processed in a way that is desired, which represents the output.

Creating a custom algorithm for computational purposes is called computer programming. Computer programming needs a programming language, which is mostly connected to the software of choice. Languages are quite similar but each has its benefits, also depending on the capabilities of the software. Well-known programming languages are, among others, Python, Java, C++ and Visual Basic for Applications (VBA).

For this research, we will zoom in on VBA for its familiarity with TKF and the researcher's knowledge. It is integrated with all Microsoft Office applications and started off with Excel, which is the application where it is most used. VBA is the underlying algorithm for the functions that can be used in Excel and creates the possibility to extend these with custom functions. The programming language itself can be found in a VBA manual and there are numerous fora about the possibilities and how to use its notations.

3.2.2 Solving methods

When designing and programming an algorithm, the way to getting the desired output must be designed and programmed too. This means that a solving method for an algorithm is a couple of extra instructions incorporated into the algorithm and can easily be made suitable to any situation, like the algorithm itself. Luckily, there are some handles that guide the programmer in the right direction, because there are a lot of ways to solve a situation. We call these handles heuristics and according to (Stelios H. Zanakis, 1981): “Operations Researchers have seen heuristics as procedures to reduce search in problem-solving activities or a means to obtain acceptable solutions within a limited computing time”. For programming a heuristic, there are a set of instructions associated with the heuristic of choice which serves as the general part. This general part can later be translated to the exact situation.

3.3 Markov decision process

3.3.1 Framework

All Markov decision processes have its fundaments in Markov chains and satisfy the Markov property. Before we discuss these processes, we shortly take a look at Markov chains.

In (Gagniuc, 2017), a Markov chain is described as follows: “A Markov chain is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the state attained in the previous event.” In Figure 5: Example of a Markov chain the state an object can be in is depicted by a circle. Between these circles arrows are placed, representing the possible transitions between states and the chances a transition takes place.

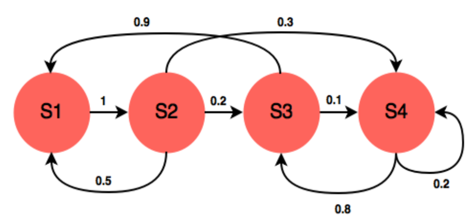

Figure 5: Example of a Markov chain

To extend this short description of Markov chains to Markov decision processes, the latter has an addition of allowing rewards and decision making. The rewards are given when moving into a new state, but cannot be all the same. Decision making overrules the chances associated with the transitions. Markov decisions processes can be used for a large portion of all the optimization problems because the chain has no limit and all specific decisions can be applied.

3.3.2 Solving methods

It is conventional that Markov decision processes that are of a larger scale, are computed by an algorithm. There are some generic algorithms available, but to make it situation specific it needs tweaking. The boundary to where algorithms take over from manual calculations is when the user finds it more effective and less time consuming. A problem with the scale described in this research is impracticable to calculate manually, so a situation specific algorithm should be made. As is discussed in section 3.2, creating an algorithm is most convenient with the use of Microsoft Office’s VBA.

3.4 Petri net

3.4.1 Framework

A Petri net is a graphical tool for the description and analysis of concurrent processes which arise in systems with many components (distributed systems) (C. A. Petri, 2008). It includes a specific notation which holds for all software and for manual description. The cornerstones for a Petri net are the following:

Tokens represent any object that travels through the described system. They pass on between *states*, indicated by *transitions*. One can place restrictions on transitions or states to represent waiting times, a fixed number of places or a different rule. When a transition of tokens is made, it is called *firing* a token.

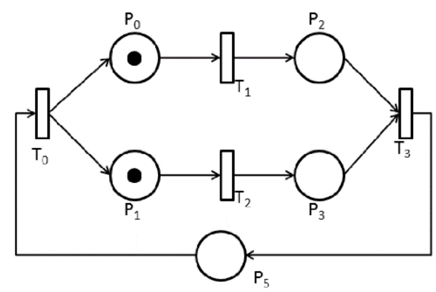

Figure 6: Example of a graphical notation of a system using Petri net

Petri net as a graphical tool creates a very intuitive and clear overview of a system, which can be useful for communication towards others. Simulation of the system is an option and creates a feeling of the flow.

3.4.2 Solving methods

Software for Petri net notations most of the times come with various analysis options. By simulating the system, a lot of different transitions can be expressed by probabilities, the steady-state of the system is easily calculated, and one can see if queues arise. There is no clear leader in the development of Petri net software, all companies have their own variant with its own options. Unlike the other frameworks, Petri net does not deliver a schedule but creates an overview of various distributions.

3.5 Concept matrix

3.5.1 Choosing the framework

To find an answer for our second sub-question and a partial motivation for the answer to the third sub-question, we make use of a concept matrix. In a concept matrix we score the frameworks by elements that we think are of importance. These elements are based on findings in the literature and preferences of TKF. The elements that were derived from findings in the literature address the points on which TKF's situation differ, but are needed to accurately describe it. Preference elements came up when discussing the possible solving methods and their implementations with the supervisors. We describe these elements in a random order below.

'The framework must be compatible with the software TKF uses'. Eventually, TKF is the environment to where the framework is implemented. Should they decide to adopt this framework, accompanied with the solving method, then instant compatibility with their software is desired. According to the supervisors of this research, it is not likely that they immediately want to invest if they do not own the software that is used. This can lead to deliverables that are not taken serious from the beginning.

‘There must be possibilities for specifying to TKF’s situation’. Frameworks can be, as described in the previous sub-sections, quite general. It is meant to serve for a whole set of problems, which can all be individually different. A framework that cannot be specified to a certain situation, result in a non-closing expression and conclusion. Another advantage of the flexibility of a framework is that it lends itself easier for experimentation. With experimentation being one of the main topics in chapter 5, the option to experiment is much desired.

‘Making a distinction between orders must be possible’. We cannot look at the orders as if they are all the same. Each order has its own specific length, thickness, setup time, and so on. Making a distinction between orders is an important factor in creating a closing expression.

‘Easy to use when solving’. We want to create a deliverable that does not need inside information or extensive knowledge. Should a new person use the deliverable, then he or she must be able to use it without consulting this research or the researcher.

‘The framework in combination with the solving method must not be time-consuming when solving’. There can be multiple ways for solving to be time-consuming. For instance, the translation between the framework and solving method is not easy. Another option is that solving takes up a lot of computing time or requires extensive input delivery from its user. It is preferable to have a solving method that does not take more than 30 seconds to compute an answer. The solving method must be quick because it becomes a burden when the user has to wait long, and then he or she is most likely to run it once and not to try different options.

Overview of concept matrix elements:

1. The framework must be compatible with the software TKF uses
2. There must be possibilities for specifying to TKF’s situation
3. Making a distinction between orders must be possible
4. Easy to use when solving
5. The framework in combination with the solving method must not be time-consuming when solving

	1	**2**	**3**	**4**	**5**
Linear programming	X	X	X	X	
Parallel machine scheduling		X	X	X	
Custom algorithm	X	X	X	X	X
Markov decision process	X	X		X	
Petri net		X		X	

Table 7: Concept matrix for scoring frameworks

The frameworks are scored by the elements in the concept matrix in 'Table 7: Concept matrix for scoring frameworks', by checking the boxes with an 'X' if the element applies to the framework. An empty box means that the element does not apply to the framework.

We can see that custom algorithm scores a perfect match and linear programming is close. The other three frameworks have two or more mismatches, leaving them unworthy for consideration. Linear programming misses the 5th element, due to the complexity with all variables and relations. Overall, creating a custom algorithm is a better fit because it can be specified more easily and it is less time consuming to set up. It can also be easily shaped in the way TKF desires. This is why we choose creating a custom algorithm as our framework and as an answer to our 2nd sub-questions.

To find the answer to sub-question 3, we must turn to the solving methods that go along with custom algorithms. In section 3.2.2, we found that heuristics serve as handles for cutting computing time. The algorithm itself is created to be a solving method, with the heuristic as a powerful addition. In the next sub-section, we describe which heuristic is best for our research.

3.5.2 **Choosing a heuristic**

Our problem is best described as a scheduling problem, sometimes called a combinatorial problem. For these problems, a certain heuristic technique applies very well. In sub-section 3.2.2 we described the definition of a heuristic.

"*Local search* is an emerging paradigm for combinatorial search, which has been recently shown to be very effective for a large number of combinatorial problems." (Moscato & Schaerf, 1998). As the title of the technique states, it is based on looking at close solutions which are in the search space. Within the search space, after defining its size, solutions are checked by iteratively stepping to neighbour solutions. Each solution is then assessed by checking the objective function, in order to maximize or minimize the outcome of this function.

Moscato & Schaerf (1998) presents three popular local search techniques. 'Hill climbing', the most simple one, is based on only accepting neighbour solutions that are better or equal, never accepting worsening moves. There are different forms of hill climbing like steepest hill climbing, random hill climbing or min-conflict hill climbing. The other two popular local search techniques are approaches for improving the hill climbing technique. 'Simulated Annealing' relies on probabilistic, memoryless decisions and 'Tabu Search' is based on the use of memory of previously visited solutions.

Because of familiarity and time planning, Simulated Annealing and Tabu Search take up more time for understanding and implementing, we choose to focus on the hill climbing technique. More specifically, 'Steepest hill climbing', because it is the most well-known form of hill climbing according to Moscato & Schaerf (1998). To add to this, the other forms are not that different in its results.

Steepest hill climbing iterates from its starting position through all neighbourhood solutions. It accepts the solution only if it is an improving solution. By completing the iteration from the starting position, the solution with the most improvement is selected as the new solution.

To visualize the technique, we sketch an example. In Figure 7: Iterating through neighbourhood from starting position the starting position is 1. It is switched with its neighbours 2, 3, 4 and 5 only to accept a solution that has a better outcome in its objective function. In our case, swapping 1 and 3 was the solution with the most improvement in the objective function. Now, we change the starting position from 1 to 2 and iterate again through all its neighbours, see Figure 8: Iterating through neighbourhood from new starting position. This process of changing the starting position and iterating through its neighbours gets repeated for all possible starting positions. We eventually end up with our local minimum or maximum which we take as the best solution.

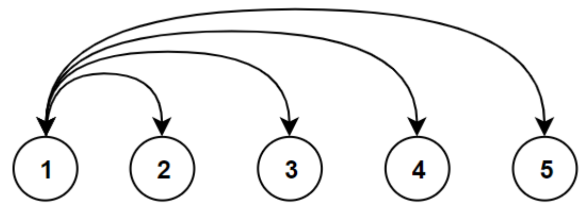

Figure 7: Iterating through neighbourhood from starting position

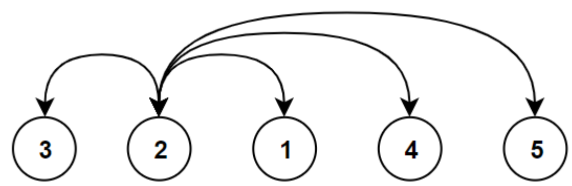

Figure 8: Iterating through neighbourhood from new starting position

To conclude this chapter with an answer to both sub-question 2 and 3, the best approach in this research is to build our own custom algorithm (sub-question 2), in combination with the steepest hill climbing technique for optimization calculations (sub-question 3).

4 Implementation of theory

This chapter describes the way the production line of TKF is translated into a conceptual model based on the findings in chapter 3. By doing so, we answer sub-question 4: ‘How to implement TKF’s situation into the framework and method?’. We start off in section 4.1 with defining our goal, meaning what purpose and layout the deliverable should possess. From there, we can describe the building blocks that together fulfill the purpose and fill in the layout. The first building block is obtaining the required data out of the database and is described in section 4.2. The second building block is creating the conceptual model in section 4.3. The conceptual model should be able to process the data from the database. Thereby it must be the result of the findings regarding the framework chosen in chapter 3, and be a foundation for realizing the findings regarding the heuristic. The latter condition is described in section 4.4 and is also our final building block.

4.1 Purpose and layout of deliverable

4.1.1 Purpose

Our goal is to translate the situation of TKF into a conceptual model, with the use of a custom algorithm. To add to that algorithm, we make use of the heuristic ‘steepest hill climbing’ for optimization calculations. If we created the conceptual model correctly, then it serves the answer to tackle our core problem which is measured by our KPI’s. Thus, we need to make sure our conceptual model quantifies the situation based on the KPI’s.

The first KPI, throughput, is measured by the number of products that is produced per unit of time. We do this by creating an overview of the orders with their time of completion. By then, it is simply dividing the number of orders produced by the time it took to produce all orders. The overview of the production is described in sub-section 4.1.2.

Lateness in delivery, our second KPI, can be measured by the difference between the set time of completion and the calculated time of completion. The calculated time of completion can be obtained from the production overview we create.

The third and last KPI, standstill of degassing rooms, is the percentage of the total production time that the degassing rooms are not in use. From our earlier mentioned overview in 4.1.2, we can see how long the degassing rooms are not in use.

Besides the purpose of measuring our KPI’s, it serves as a platform on which TKF obtains schedules, should they decide to use it. This adds a new purpose to our conceptual model, namely the model being a tool that provides overview on production scheduling and can optimize the situation when desired.

4.1.2 Layout

The layout of the conceptual model must include easy access for reviewing the KPI’s. When taking it from the perspective of a tool for TKF, we want a simple layout that speaks for itself. Layouts for the sheet in the excel file can be found in ‘Appendix B: Layout conceptual model’. In the excel file we have the following sheets:

1. CDCC

Per product, we have the ability to lock it so steepest hill climbing will not consider solutions in which this product is swapped. Then we have about 5 columns with information about the product, useful for interpreting the obtained schedule. The length, processing time and setup time provide information for calculations. In the column named priority, the priority given by TKF is displayed and products are sorted to this value. The column value represents the short degassing time and the delivery date end product is incorporated for calculations in the 'Due Date' sheet. At last, we have the column 'Order' which is a tool for the execution of the steepest hill climbing heuristic.

2. Degassing

The sheet about degassing displays the same product information as the CDCC sheet. In the column 'Which degassing room?' the user can indicate if a certain product is present in 1 of the 2 degassing rooms. Should this be the case, the user can fill in the number of hours it is already degassing in column G.

3. Schedule

This sheet provides the option to execute the calculations for the conceptual model, as well as for the steepest hill climbing heuristic. When executed, it provides an overview of the products that passed the CDCC, Degassing room 1, Degassing room 2 or no degassing room at all. All relevant product information is given, as well as the time it started insulating and/or degassing or finished insulating and/or degassing.

4. Due date

This sheet gives an overview of the products, with its product information, on when it is finished degassing and when the end product is expected to be delivered. Based on these dates, the difference is calculated.

5. Exsion

The Exsion sheet provides the tool for retrieving the right data from the database. It has 1 tool for the products at the CDCC and 1 tool for the products in the degassing stage.

6. Temporary copy

A temporary copy is made as a backup for the heuristic to compare the initial situation with the new situation.

7. Initial copy

The initial copy is made before orders are swapped by the heuristic. It makes it possible to return to the initial situation and to run the conceptual model after the heuristic ran.

8. Parameters

In this sheet, a table is provided with parameters that could change. It makes it possible to easily change the situation without editing the full code.

4.2 Information from database

At TKF, almost every productional action and all product information is recorded and stored in a database. This database can be accessed by employees via an ERP system. The software is called Navision and is used throughout all departments. It is used to find information, see what is currently in production or to release and remove products. In addition to Navision, there is Exsion. Exsion is a paid tool in Microsoft Excel, that has a couple of functions regarding getting information out of a database. With the right queries, Exsion can merge different tables, product and production information to the user's likes. It serves as a bridge between the database and Excel and can save the user a considerable amount of time.

Together with the supervisors of TKF, in particular Tom Bijen, we have established the elements and filters that are necessary for our conceptual model, which we will describe below. There are also some elements that are of importance for TKF to be present in the tool. Most important, is that we get all the information of the orders that are scheduled for insulation or are at the CDCC, and the products that are degassing. We shortly discuss the two Exsion queries that we use for our conceptual model and tool below. These queries can be found in Appendix C: Exsion queries.

4.2.1 CDCC

We want to request the data of the orders that are currently at the CDCC, and the orders that are in line for insulation. Figure 16: Exsion query for CDCC results in Appendix C: Exsion queries shows the query that we use for these products. We filter out the products with a length shorter than 200 meters because these are test reels or remnants from the actual order. Furthermore, we ignore the products that have a degassing time lower than 50 hours, denoted by 'Waarde'. These orders do not belong to this production line. An order can only show up if it is finished at its previous operation, filtering out the orders that are scheduled for the long term and have not yet passed the wire drawing.

We sort the results to their priority, which is assigned by the production planner. Should multiple orders have the same priority, a second filter puts them in order of shortest delivery date of the end product.

4.2.2 Degassing rooms

With the query displayed in Figure 17: Exsion query for degassing results, we request the data of the orders that are currently degassing. This means that they can either be in degassing room 1, degassing room 2 or at the storage space for degassing. From the information in the database, we cannot make a distinction about the orders locations. As it is done with the CDCC query, we do not want the orders with a degassing time lower than 50 hours at degassing too.

4.3 Conceptual model

4.3.1 Visual Basic for Applications

VBA is an add-on for Microsoft Office and in our case Excel, as we mentioned earlier in section 3.2.1. We use it to automatize our calculations and to extend the functions of Excel. VBA projects are build up from modules, which can be seen as the page where the code is written down. Within a module, subs and functions are defined. Subs are a demarcation of a couple of actions described by code, functions return a value. Variables can be declared in a sub or function, but can also be made global for repetitive reasons. In section 4.3.2 we describe the structure of our declared variables and then we describe the structure of our codes on the basis of our subs in section 0.

4.3.2 Variables

We discuss the variables that we use globally, meaning that they keep their value if we switch to another sub. The variables that are used globally mostly store the information of the orders that we need for calculations and display in a schedule. Others are for keeping track of time, occupation of degassing rooms, place in the production line, etcetera.

Order information is stored in arrays. An array is a group of variables and can have one or more dimensions. The result of this can be seen in 'Table 8: Arrays of product information variables'. Products range from 0 to C, with C being the sum of all products minus 1 because the counting starts at 0.

Variable ProductNumber

This variable is a 10 digit number with the first 6 related to the product and the last 4 specific to the part of the order.

Variable Article(1, 2, 3 and 4)

The article variable is the only one stored in a two-dimensional array. This is because there are 4 different descriptions for the same product. They tell what material is used for insulation, the thickness of layers, the voltage class and many more.

Variable ProductionTime

With the production time in our code, we define the number of hours a product still has to be insulated. This number is fixed before insulating and goes down to 0 when in 'production' at the CDCC. Products that are already insulated have the variable set to 0.

Variable SetupTime

Setup time depicts the number of hours that is needed to set up the CDCC for another type of order. The setup time assigned to the first product of an order, because that is when the setup takes place. All the other products of that order have the variable set to 0. Products that are already insulated have the variable set to 0.

Variable DegassingTimeShort

This variable represents the number of hours a product needs to degas if it is placed in 1 of the 2 degassing rooms.

Variable DegassingTimeLong

This variable represents the number of hours a product needs to degas if it is not placed in 1 of the 2 degassing rooms. Because this information cannot be retrieved from the database, it is derived from the variable DegassingTimeShort and based on the values TKF uses.

Product	Product Number	Article (1)	Article (2)	Article (3)	Article (4)	Productio n Time	Setup Time	Degassing Time Short	Degassing Time Long
0									
1									
2									
…									
C – 2									
C – 1									
C									

Table 8: Arrays of product information variables

Variable NrProductsDegas

To figure out how many products are in a queue waiting to degas, we use this variable as a counter.

Variable Degassingroom1 and Degassingroom2

With these 2 variables we can differentiate how many products are in degassing room 1 and 2.

Variable DegasTime1 and DegasTime2

These 2 variables indicate how many hours there are still left of the degassing process in degassing room 1 and 2.

4.3.3 Subs

In this subsection about subs, we discuss the functions of the subs and provide overview through flowcharts that can be found in Appendix D: Flowcharts conceptual model.

The sequence in which the subs are processed depends on the place in the code where the subs are called. All subs are linked, which means that we only have 1 to start the whole sequence. A separate module called ‘Button’, serves as this initiator. Figure 15: First 25 rows of conceptual model, schedule sheet part 1 shows the button in cell A1 that triggers this module. When pressed, subsequently the following subs are called: ‘ConvertToNumber’, ‘ClearResults’, ‘AllProducts’, ‘AssignArrays’ and ‘Calculation’. These subs are all coded in another module called ‘Conceptual’, which we discuss below one at a time.

Sub ConvertToNumber

When we collect the data from the database, not all information is in the right format. The product order number and shortest degassing time are delivered as in a text format. This sub changes the format to our standard format which is a number. By doing this, we can use these numbers for further calculations. For an overview on the place of the sub in the sequence, see: Figure 18: Flowcharts Sub "Convert To Number", "Clear Results", "All Products" and "Assign Arrays".

Sub ClearResults

This sub sets a couple of variables to its primal state and others to, for example, the current time and date. Especially when using the tool multiple times, the previous data can still be present in the document, disturbing new calculations. This is why we need to clear most of the results and set variables again. For an overview on the place of the sub in the sequence, see: Figure 18: Flowcharts Sub "Convert To Number", "Clear Results", "All Products" and "Assign Arrays".

Sub AllProducts

Sub “AllProducts” checks how many products there are retrieved from the database, and thus in our production line. By doing this, we obtain a value for variable “C”, which is necessary for defining our arrays as described in sub-section 4.3.2. For an overview on the place of the sub in the sequence, see: Figure 18: Flowcharts Sub "Convert To Number", "Clear Results", "All Products" and "Assign Arrays".

Sub AssigningArrays

This relatively large sub assigns values to all our places in the arrays. Once this is done for both products at and before the CDCC and at degassing, products get checked for being in one of the two degassing rooms. It is important that the user of this tool specifies for which products this holds, and if so, how long these products are already degassing. This ensures a more accurate calculation and solution. In Figure 18: Flowcharts Sub "Convert To Number", "Clear Results", "All Products" and "Assign Arrays" the actions within the sub are displayed.

Sub Calculation

The sub “Calculation” has its main task as a distribution station, constantly checking the situation and determining what sub needs to be called. Figure 19: Flowchart Sub "Calculation" displays the flowchart of how the subs are all connected. The subs are displayed as a simple square accompanied by its title, because of complexity issues. For a detailed view on the specific subs, please read the corresponding description below.

Once all the degassing times in the array are summed up and yield 0, the loop is finished and thus the sequence of subs.

Sub ProductionAndSettingTime

We use this sub to determine and adjust the production and setting times of all products. Figure 20: Flowchart Sub "Production and Setting Time" gives an overview of the actions within this sub.

Sub TwoEmpty

In the situation that both degassing rooms are empty, this sub is called. It finds the products that need the longest degassing time and puts them in degassing room 1. Once this room is full, the subsequent products are put in degassing room 2 until this room is full too. We have 2 figures that display the flowcharts, because of margin issues. The flowchart is split into a left side; Figure 21: Left side of flowchart Sub "Two Empty"’ and a right side; Figure 22: Right side of flowchart Sub "Two Empty". After the two degassing rooms are filled, warm-up and cooling down time is added.

Sub SecondEmpty

This sub is called when there are not enough products to fill both degassing rooms or when degassing room 1 is already degassing. It fills the room in the same order the other subs do, based on longest degassing time of a product. See Figure 23: Flowchart Sub "Second Empty" for its associated flowchart.

Sub FirstEmpty

Adjacent to the previous sub, this sub too is called when there are not enough products to fill both degassing rooms or when degassing room 2 is already degassing. It fills the room in the same order the other subs do, based on longest degassing time of a product. See Figure 24: Flowchart Sub "First Empty" for its associated flowchart.

Sub TwoFull

In the case of both degassing rooms being full, 1 hour is subtracted from both degassing times. See Figure 25: Flowchart Sub "Two Full".

Sub DegassingTime

The sub "DegassingTime" evaluates and adjusts the degassing times per simulated hour. Whenever a degassing time is under the shortest degassing time in a degassing room, its time gets set to 0 and is displayed in the schedule as 'degassed without a degassing room'. Figure 26: Flowchart Sub "Degassing Time" displays the subsequent actions.

Sub NrOfProductsToDegas

This sub defines the waiting line in which all products are that need degassing. This gives an indication for completely filling a degassing room when it is done degassing. See Figure 27: Flowchart Sub "Nr. Of Products To Degas".

4.4 Steepest hill climbing

4.4.1 Subs

The heuristic steepest hill climbing is coded in a separate module and must be called via a different button. When pressing the button 'Heuristic' on the worksheet 'Schedule', a sequence of two subs is started. How the actions and the subs are linked can be found in Appendix E: Flowcharts steepest hill climbing. The heuristic is coded in such a way that it needs the conceptual model when started, but not the other way around. Because of the relatively large computational time that is related to the heuristic, we turn off screen updating to reduce the length.

Sub Priorities

This sub runs the conceptual model first to have a base on which it can generate a possible better solution. From there on, orders get a priority assigned to make it easier to swap them. All products in an order get the same priority. A copy is made from the original schedule, after which the sub "Sorting" is called. A detailed description can be found in Figure 28: Flowchart Sub "Priorities".

Sub Sorting

The sub "Sorting" changes the way the orders are prioritized and calculates the schedule with each change. A copy is made if the situation is improved, so in the end we have the maximum local schedule. The actions in the sub can be viewed in Figure 29: Flowchart Sub "Sorting".

5 Results and experimentations

Chapter 5 describes the results and scores of our KPI's on 8 different situations. Section 5.1 and 5.2 display the results of the conceptual model and steepest hill climbing, respectively. After we have discussed these results, we experiment and alter the conditions to find out their effects. Section 5.3 en Section 5.4 describe the two experiments that are going to do. To conclude this chapter, section 5.5 makes a comparison between the findings to see the effects of the conditions.

Basically we describe three situations in this chapter. The so-called normal situation, and two experiments. At each of these three situations we want to create a schedule and derive values for our KPIs with the conceptual model and the steepest hill climbing. Per situation we base our findings on 8 different points in time, on which a download from the database is made. In all the tables in this chapter they are called situations, described by their date of downloading and represent the situation at that exact moment.

The first experiment in section 5.3 has the rule that there cannot be any standstill of the degassing rooms. We use this rule to calculate the conceptual and steepest hill climbing. By conducting this experiment, we want to get a feeling whether it is worth the wait for products that have yet to be insulated to completely fill the degassing room.

The second experiment is described in section 5.4 and has the rule that the first two orders at the CDCC must remain in its position. These cannot be swapped during the steepest hill climbing method. The conceptual schedule will provide us the same schedule as in the normal situation, so we just use the situation with steepest hill climbing. We lock these two first orders based on the unwritten rule that most likely these are already fully prepared to be insulated, or maybe are already under operation at the CDCC.

5.1 Conceptual model

5.1.1 KPI: Throughput

The conceptual model is based on the situation as it is right now, just after the download from the database. It should largely cover reality, to which we can make changes with for example a heuristic. Table 9: Throughput of conceptual model displays all the information needed to calculate the throughput per situation. The number of products is divided by the difference between the start and end date, to get the throughput. Note that this is the number of products (reels) per day, and has nothing to do with the number of orders per day because orders differ from size.

Situation	Date started	Date ended	Difference	Number of products	Throughput Products/Day
17-07-19	17-07-19, 17h	31-07-19, 11h	13d 18h	46	**3,345**
24-07-19	24-07-19, 10h	02-08-19, 22h	9d 12h	32	**3,368**
26-07-19	26-07-19, 10h	06-08-19, 10h	11d 0h	52	**4,727**
30-07-19	30-07-19, 10h	10-08-19, 19h	11d 9h	42	**3,692**
05-08-19	05-08-19, 08h	13-08-19, 11h	8d 3h	30	**3,692**
07-08-19	07-08-19, 10h	14-08-19, 00h	6d 14h	18	**2,734**
16-08-19	16-08-19, 11h	29-08-19, 20h	13d 9h	44	**3,290**
21-08-19	21-08-19, 07h	05-09-19, 05h	14d 22h	46	**3,084**

Table 9: Throughput of conceptual model

5.1.2 KPI: Lateness in delivery

For our 8 situations, we measure lateness in delivery through 3 variables. Table 10: Lateness in delivery conceptual model displays the number of products that are late, the sum of that lateness and the average lateness. Note that the expected delivery date of the end product is the finish time degassing plus 10 days. This holds for the experiments too.

When observing the table, we can see that on average products are delivered fairly on time. In reality, each order that is delivered too late is a problem that has to be solved. We therefore must take a look at the number of products late per the total number of products. From that we can see that in some cases, almost half of the products are expected to be delivered too late. This is a statistic which can provide us a good insight in performance when comparing to steepest hill climbing and the experiments.

Situation	**Number of products late per total products**	**Sum of lateness (days, hours)**	**Average lateness (days, hours)**
17-07-19	0/31	0d 0h	-20d 7h
24-07-19	5/20	17d 16h	-20d 14h
26-07-19	16/34	70d 23h	-26d 1h
30-07-19	17/31	30d 0h	-27d 1h
05-08-19	9/15	58d 6h	-11d 13h
07-08-19	0/6	0d 0h	-37d 21h
16-08-19	37/43	242d 2h	1d 22h
21-08-19	25/39	205d 17h	1d 16h

Table 10: Lateness in delivery conceptual model

5.1.3 KPI: Standstill of degassing rooms

The standstill of degassing rooms is calculated per degassing room. The total time over which the standstill is measured goes from the moment that the schedule starts until that particular degassing room is finished degassing. Standstill times are the times in the total time in which a degassing room is not warming up, cooling down or in operation. See Table 11: Standstill of degassing rooms conceptual model for the numbers. Degassing room 1 has 5,3% less standstill, this is because this degassing room has priority over degassing room 2 when both degassing rooms are empty.

	Degassing room 1			Degassing room 2			Total
Situation	**Total time**	**Standstill time**	**Percentage**	**Total time**	**Standstill time**	**Percentage**	**Average percentage**
17-07-19	5d 23h	0d 0h	0,0%	9d 11h	0d 0h	0,0%	0,0%
24-07-19	5d 23h	0d 0h	0,0%	6d 16h	0d 17h	10,6%	5,3%
26-07-19	9d 11h	0d 0h	0,0%	5d 23h	0d 0h	0,0%	0,0%
30-07-19	2d 11h	0d 0h	0,0%	7d 6h	0d 17h	9,8%	4,9%
05-08-19	3d 1h	0d 0h	0,0%	5d 23h	0d 0h	0,0%	0,0%
07-08-19	3d 1h	0d 0h	0,0%	3d 18h	1d 7h	34,4%	17,2%
16-08-19	8d 14h	2d 15h	30,6%	11d 14h	2d 3h	18,3%	24,5%
21-08-19	3d 21h	1d 10h	36,6%	12d 23h	0d 0h	0,0%	18,3%
Average	**-**	**-**	**8,4%**	**-**	**-**	**9,1%**	**8,8%**

Table 11: Standstill of degassing rooms conceptual model

5.2 Steepest hill climbing

5.2.1 KPI: Throughput

For calculating the throughput with steepest hill climbing, we used the same method as for our conceptual model. Table 12: Throughput of steepest hill climbing displays the used information and resulting throughput.

Now that we know the throughput of the conceptual model and of the steepest hill climbing heuristic, it is useful to make a comparison in order to get a feeling of the impact of the heuristic. Per situation, we put the throughput of the steepest hill climbing next to the throughput of the conceptual model and calculate the percentage change. This can be seen in Table 13: Comparison throughput of conceptual model and steepest hill climbing, which has in its last row a comparison of the averages. On average, based on 8 situations, throughput is 21,8% higher when a schedule is made by steepest hill climbing. This means that the production schedule from steepest hill climbing can produce the same number of products in 82,1% of the time it takes for the conceptual model. If we take an hour to represent the time, steepest hill climbing saves 10,7 minutes per hour.

Situation	**Started**	**Ended**	**Difference**	**Number of products**	**Throughput Products/Day**
17-07-19	17-07-19, 17h	27-07-19, 04h	9d 11h	46	**4,863**
24-07-19	24-07-19, 10h	31-07-19, 14h	7d 4h	32	**4,465**
26-07-19	26-07-19, 10h	05-08-19, 02h	9d 16h	52	**5,379**
30-07-19	30-07-19, 10h	10-08-19, 02h	10d 16h	42	**3,938**
05-08-19	05-08-19, 08h	11-08-19, 07h	5d 23h	30	**5,035**
07-08-19	07-08-19, 10h	13-08-19, 15h	6d 5h	18	**2,900**
16-08-19	16-08-19, 11h	28-08-19, 12h	12d 01h	44	**3,654**
21-08-19	21-08-19, 07	02-09-19, 10h	12d 03h	46	**3,794**

Table 12: Throughput of steepest hill climbing

Situation	**Throughput Conceptual model**	**Throughput Steepest Hill Climbing**	**Throughput change (%)**
17-07-19	3,345	4,863	45,4%
24-07-19	3,368	4,465	32,6%
26-07-19	4,727	5,379	13,8%
30-07-19	3,692	3,938	6,4%
05-08-19	3,692	5,035	36,4%
07-08-19	2,734	2,900	6,1%
16-08-19	3,290	3,654	14,1%
21-08-19	3,084	3,794	23,0%
Average	**3,492**	**4,254**	**21.8%**

Table 13: Comparison throughput of conceptual model and steepest hill climbing

5.2.2 KPI: Lateness in delivery

Just as we did with our conceptual model, we display our lateness in delivery through the same 3 variables in Table 14: Lateness in delivery steepest hill climbing. We now can compare the two to see if there are any major differences.

Table 15: Comparison of lateness between conceptual and steepest hill climbing places the conceptual model (C), next to steepest hill climbing (S) and let us see the difference (D). We can see that the steepest hill climbing can cause new peaks in the number of products that are delivered late. In the schedule that TKF creates, this lateness is taken into account and results in the findings for our conceptual model. With the steepest hill climbing on the other hand this is not the case, which can cause these new peaks. On average, the products are delivered earlier with steepest hill climbing.

Situation	**Number of products late per total products**	**Sum of lateness (days, hours)**	**Average lateness (days, hours)**
17-07-19	0/31	0d 0h	-21d 0h
24-07-19	5/20	26d 12h	-21d 0h
26-07-19	16/34	42d 17h	-26d 16h
30-07-19	20/31	56d 11h	-27d 05h
05-08-19	9/15	58d 19h	-11d 18h
07-08-19	0/6	0d 0h	-37d 19h
16-08-19	34/43	265d 4h	2d 5h
21-08-19	28/39	163d 23h	1d 3h

Table 14: Lateness in delivery steepest hill climbing

Situation	Number of products late per total products			Sum of lateness (days, hours)			Average lateness (days, hours)		
	C	S	D	C	S	D	C	S	D
17-07-19	0/31	0/31	0	0d 0h	0d 0h	0d 0h	-20d 7h	-21d 0h	-0d 17h
24-07-19	5/20	5/20	0	17d 16h	26d 12h	8d 20h	-20d 14h	-21d 0h	-0d 10h
26-07-19	16/34	16/34	0	70d 23h	42d 17h	-28d 6h	-26d 1h	-26d 16h	-0d 15h
30-07-19	17/31	20/31	3	30d 0h	56d 11h	26d 11h	-27d 1h	-27d 05h	-0d 4h
05-08-19	9/15	9/15	0	58d 6h	58d 19h	0d 13h	-11d 13h	-11d 18h	-0d 5h
07-08-19	0/6	0/6	0	0d 0h	0d 0h	0d 0h	-37d 21h	-37d 19h	0d 2h
16-08-19	37/43	34/43	-3	242d 2h	265d 4h	23d 2h	1d 22h	2d 5h	-0d 7h
21-08-19	25/39	28/39	3	205d 17h	163d 23h	-41d 18h	1d 16h	1d 3h	0d 13h

Table 15: Comparison of lateness between conceptual and steepest hill climbing

5.2.3 KPI: Standstill of degassing rooms

This KPI is calculated and displayed in the same way as with the conceptual model, see Table 16: Standstill of degassing rooms steepest hill climbing. A comparison between the conceptual model and steepest hill climbing is made in Table 17: Comparison standstill of degassing rooms conceptual and steepest hill climbing.

In the comparison table, we depict the conceptual model (C), steepest hill climbing (S) and the difference (D). We can see that degassing room 1 has less standstill than degassing room 2, mainly because in the case that both need to be filled, degassing room 1 has priority. Another result that stands out is that steepest hill climbing leads to 7,6% more standstill of degassing rooms on average. We intuitively expect a more efficient use of degassing rooms whenever a schedule has a higher throughput. That is why we compare the total times of the conceptual model and the steepest hill climbing in Table 28 in Appendix F: Comparison total run times. From that we see that on average the total time with steepest hill climbing is longer than with the conceptual model. A possible explanation for this is discussed in section 5.5.

	Degassing room 1			Degassing room 2			Total
Situation	**Total time**	**Standstill time**	**Percentage**	**Total time**	**Standstill time**	**Percentage**	**Average percentage**
17-07-19	9d 11h	0d 0h	0,0%	6d 15h	0d 16h	10,1%	5,1%
24-07-19	5d 23h	0d 0h	0,0%	7d 4h	1d 5h	16,9%	8,5%
26-07-19	9d 16h	0d 5h	2,2%	7d 16h	1d 17h	22,3%	12,3%
30-07-19	2d 11h	0d 0h	0,0%	11d 16h	0d 15h	5,4%	2,7%
05-08-19	3d 1h	0d 0h	0,0%	5d 23h	0d 0h	0,0%	0,0%
07-08-19	3d 1h	0d 0h	0,0%	3d 9h	0d 22h	27,2%	13,6%
16-08-19	12d 1h	7d 2h	58,8%	10d 16h	1d 7h	12,1%	35,5%
21-08-19	9d 18h	3d 20h	39,3%	10d 18h	3d 7h	30,6%	35,0%
Average	**-**	**-**	**12,5%**	**-**	**-**	**15,6%**	**14,1%**

Table 16: Standstill of degassing rooms steepest hill climbing

	Degassing room 1			Degassing room 2			Total		
Situation	**C**	**S**	**D**	**C**	**S**	**D**	**C**	**S**	**D**
17-07-19	0,0%	0,0%	0,0%	0,0%	10,1%	10,1%	0,0%	5,1%	5,1%
24-07-19	0,0%	0,0%	0,0%	10,6%	16,9%	6,3%	5,3%	8,5%	3,2%
26-07-19	0,0%	2,2%	2,2%	0,0%	22,3%	22,3%	0,0%	12,3%	12,3%
30-07-19	0,0%	0,0%	0,0%	9,8%	5,4%	-4,8%	4,9%	2,7%	-2,2%
05-08-19	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
07-08-19	0,0%	0,0%	0,0%	34,4%	27,2%	-7,2%	17,2%	13,6%	-3,6%
16-08-19	30,6%	58,8%	28,2%	18,3%	12,1%	-6,2%	24,5%	35,5%	11,0%
21-08-19	36,6%	39,3%	2,6%	0,0%	30,6%	30,6%	18,3%	35,0%	35,0%
Average	**8,4%**	**12,5%**	**4,1%**	**9,1%**	**15.6%**	**6,4%**	**8,8%**	**14,1%**	**5,3%**

Table 17: Comparison standstill of degassing rooms conceptual and steepest hill climbing

5.3 Experiment: No standstill degassing rooms

With no standstill of degassing rooms, we have a situation that whenever a degassing room is empty, it is directly filled with the waiting available products. The only condition is that we do not start a degassing room without products, because this would in no case be beneficial. In the sub 'Calculation', we relax the number of products to degas which makes it possible to fill the degassing room partially.

5.3.1 KPI: Throughput conceptual model

In Table 18: Throughput of conceptual model with no standstill the results for the conceptual model with no standstill are displayed.

We can now compare the throughput of the conceptual model with the conceptual model that allows no standstill. Table 19: Comparison throughput conceptual model and conceptual model with no standstill shows also the difference, which on average 10,6% higher and has no decrease in any situation.

Situation	**Started**	**Ended**	**Difference**	**Number of products**	**Throughput Products/Day**
17-07-19	17-07-19, 17h	28-07-19, 00h	10d 7h	46	**4,470**
24-07-19	24-07-19, 10h	02-08-19, 21h	9d 11h	32	**3,383**
26-07-19	26-07-19, 10h	06-08-19, 10h	11d 0h	52	**4,727**
30-07-19	30-07-19, 10h	09-08-19, 07h	10d 21h	42	**3,862**
05-08-19	05-08-19, 08h	11-08-19, 21h	6d 13h	30	**4,586**
07-08-19	07-08-19, 10h	13-08-19, 09h	5d 23h	18	**3,021**
16-08-19	16-08-19, 11h	29-08-19, 20h	13d 9h	44	**3,290**
21-08-19	21-08-19, 07	03-09-19, 06h	12d 23h	46	**3,550**

Table 18: Throughput of conceptual model with no standstill

Situation	Throughput conceptual model	Throughput conceptual model with no standstill	Difference
17-07-19	3,345	4,470	33,6%
24-07-19	3,368	3,383	0,4%
26-07-19	4,727	4,727	0,0%
30-07-19	3,692	3,862	4,6%
05-08-19	3,692	4,586	24,2%
07-08-19	2,734	3,021	10,5%
16-08-19	3,290	3,290	0,0%
21-08-19	3,084	3,550	15,1%
Average	**3,492**	**3,861**	**10,6%**

Table 19: Comparison throughput conceptual model and conceptual model with no standstill

5.3.2 KPI: Throughput steepest hill climbing

The results of steepest hill climbing with no standstill of degassing rooms are displayed in 'Table 20: Throughput of steepest hill climbing with no standstill'.

Now that we have the calculated throughput per situation with mentioned adjustment, we can compare the throughput between steepest hill climbing and steepest hill climbing with no standstill of degassing rooms. See 'Table 21: Comparison throughput steepest hill climbing and no standstill'. As we can see from this table, the difference in the average throughput time -1,9% and is quite small. What this means is that based on 8 situations, the steepest hill climbing with standstill of degassing rooms allowed results in a higher throughput on average.

Situation	Started	Ended	Difference	Number of products	Throughput Products/Day
17-07-19	17-07-19, 17h	27-07-19, 04h	9d 11h	46	**4,863**
24-07-19	24-07-19, 10h	02-08-19, 17h	9d 7h	32	**3,444**
26-07-19	26-07-19, 10h	05-08-19, 02h	8d 9h	52	**6,209**
30-07-19	30-07-19, 10h	08-08-19, 19h	10d 16h	42	**3,938**
05-08-19	05-08-19, 08h	11-08-19, 13h	6d 5h	30	**4,832**
07-08-19	07-08-19, 10h	13-08-19, 09h	5d 23h	18	**3,021**
16-08-19	16-08-19, 11h	29-08-19, 06h	12d 19h	44	**3,440**
21-08-19	21-08-19, 07	02-09-19, 23h	12d 16h	46	**3,632**

Table 20: Throughput of steepest hill climbing with no standstill

Situation	Throughput steepest hill climbing	Throughput steepest hill climbing no standstill	Difference
17-07-19	4,863	4,863	0,0%
24-07-19	4,465	3,444	- 22,9%
26-07-19	5,379	6,209	15,4%
30-07-19	3,938	3,938	0,0%
05-08-19	5,035	4,832	- 4,0%
07-08-19	2,900	3,021	4,2%
16-08-19	3,654	3,440	-6,2%
21-08-19	3,794	3,632	-4,5%
Average	**4,254**	**4,172**	**-1,9%**

Table 21: Comparison throughput steepest hill climbing and no standstill

5.3.3 KPI: Lateness in delivery

In this experiment, we compare the lateness in delivery with that of the steepest hill climbing of the non-experiment situation. In 'Table 22: Comparison lateness in delivery, steepest hill climbing and no standstill' we can see the results of steepest hill climbing (S), steepest hill climbing with no standstill in degassing rooms allowed (N) and their difference (D). The difference in averages is not large and stays within the limit of a day.

Situation	**Number of products late**			**Sum of lateness (days, hours)**			**Average lateness (days, hours)**		
	S	N	D	S	N	D	S	N	D
17-07-19	0/31	0/31	0	0d 0h	0d 0h	0d 0h	-21d 0h	-20d 18h	0d 6h
24-07-19	5/20	5/20	0	26d 12h	25d 13h	-0d 23h	-21d 0h	-20d 4h	0d 20h
26-07-19	16/34	16/34	0	42d 17h	62d 2h	19d 9h	-26d 16h	-26d 16h	0d 0h
30-07-19	20/31	12/31	-8	56d 11h	48d 10h	-8d 1h	-27d 05h	-27d 20h	-0d 15h
05-08-19	9/15	9/15	0	58d 19h	33d 13h	-25d 6h	-11d 18h	-11d 14h	0d 4h
07-08-19	0/6	0/6	0	0d 0h	0d 0h	0d 0h	-37d 19h	-37d 8h	0d 11h
16-08-19	34/43	34/43	0	265d 4h	233d 8h	-31d 20h	2d 5h	1d 23h	-0d 6h
21-08-19	28/39	27/39	-1	163d 23h	221d 6h	57d 7h	1d 3h	1d 17h	0d 14h

Table 22: Comparison lateness in delivery, steepest hill climbing and no standstill

5.4 Experiment: First two orders locked

By locking the first two orders, they cannot be swapped with the steepest hill climbing heuristic. This results in fewer possible solutions. For this experiment we do not run the conceptual model, because this results in the same output as in sub-section 5.1.1. Thus, we only look at the steepest hill climbing to see the effects.

5.4.1 KPI: Throughput steepest hill climbing

In 'Table 23: Throughput of steepest hill climbing with first two orders locked' the available information for the throughput is displayed.

'Table 24: Comparison throughput steepest hill climbing and first two orders locked' gives the comparison between the normal steepest hill climbing with and with the first two orders locked. We can see that the average throughput time is going down by 10,5%, possibly because of the fewer solution options.

Situation	Started	Ended	Difference	Number of products	Throughput Products/Day
17-07-19	17-07-19, 17h	28-07-19, 10h	10d 17h	46	**4,300**
24-07-19	24-07-19, 10h	02-08-19, 22h	9d 12h	32	**3,368**
26-07-19	26-07-19, 10h	06-08-19, 10h	11d 0h	52	**4,727**
30-07-19	30-07-19, 10h	09-08-19, 10h	10d 0h	42	**4,2**
05-08-19	05-08-19, 08h	13-08-19, 00h	7d 16h	30	**3,913**
07-08-19	07-08-19, 10h	14-08-19, 00h	6d 14h	18	**2,734**
16-08-19	16-08-19, 11h	29-08-19, 09h	12d 22h	44	**3,407**
21-08-19	21-08-19, 07	02-09-19, 08h	12d 1h	46	**3,820**

Table 23: Throughput of steepest hill climbing with first two orders locked

Situation	Throughput steepest hill climbing	Throughput steepest hill climbing with first two orders locked	Difference
17-07-19	4,863	4,300	-11,6%
24-07-19	4,465	3,368	-24,6%
26-07-19	5,379	4,727	-12,1%
30-07-19	3,938	4,2	6,7%
05-08-19	5,035	3,913	-22,3%
07-08-19	2,900	2,734	-5,7%
16-08-19	3,654	3,407	-6,8%
21-08-19	3,794	3,820	0,7%
Average	**4,254**	**3,809**	**-10,5%**

Table 24: Comparison throughput steepest hill climbing and first two orders locked

5.4.2 KPI: Lateness in delivery steepest hill climbing

In this experiment, we compare the lateness in delivery in 'Table 25: Comparison lateness in delivery, steepest hill climbing and first two locked'. Steepest hill climbing (S) is compared with the steepest hill climbing from this experiment (L) and the difference is calculated (D). From the table, we can state that there are no big changes, except that the average lateness tends be to less early.

Situation	Number of products late			Sum of lateness (days, hours)			Average lateness (days, hours)		
	S	L	D	S	L	D	S	L	D
17-07-19	0/31	2/31	2	0d 0h	0d 9h	0d 9h	-21d 0h	-20d 9h	0d 15h
24-07-19	5/20	5/20	0	26d 12h	17d 6h	-9d 6h	-21d 0h	-20d 4h	0d 20h
26-07-19	16/34	16/34	0	42d 17h	70d 23h	28d 6h	-26d 16h	-26d 1h	0d 15h
30-07-19	20/31	16/31	-4	56d 11h	47d 1h	-9d 10h	-27d 05h	-27d 0h	0d 5h
05-08-19	9/15	9/15	0	58d 19h	54d 7h	-4d 12h	-11d 18h	-11d 10h	0d 8h

07-08-19	0/6	0/6	0	0d 0h	0d 0h	0d 0h	-37d 19h	-37d 21h	-0d 2h
16-08-19	34/43	37/43	3	265d 4h	211d 8h	-53d 20h	2d 5h	1d 21h	-0d 8h
21-08-19	28/39	23/39	-5	163d 23h	185d 16h	21d 17h	1d 3h	1d 11h	0d 10h

Table 25: Comparison lateness in delivery, steepest hill climbing and first two locked

5.4.3 KPI: Standstill of degassing rooms

The standstill of degassing rooms in the situation where the first two orders are locked is displayed in 'Table 26: Standstill of degassing rooms first two orders locked steepest hill climbing'.

Naturally, we want to compare these results with the results from steepest hill climbing. The comparison can be found in 'Table 27: Comparison standstill of degassing rooms, steepest hill climbing and first two orders locked'. We can see that with this experiment, on average the standstill time of the degassing rooms has gone down with 4,6%.

	Degassing room 1			**Degassing room 2**			**Total**
Situation	**Total time**	**Standstill time**	**Percentage**	**Total time**	**Standstill time**	**Percentage**	**Average percentage**
17-07-19	9d 11h	0d 0h	0,0%	5d 23h	0d 0h	0,0%	0,0%
24-07-19	5d 23h	0d 0h	0,0%	6d 16h	0d 17h	10,6%	5,3%
26-07-19	9d 11h	0d 0h	0,0%	5d 23h	0d 0h	0,0%	0,0%
30-07-19	2d 11h	0d 0h	0,0%	7d 6h	0d 17h	9,8%	4,9%
05-08-19	3d 1h	0d 0h	0,0%	5d 23h	0d 0h	0,0%	0,0%
07-08-19	3d 1h	0d 0h	0,0%	3d 18h	1d 7h	34,4%	17,2%
16-08-19	8d 14h	2d 3h	24,8%	12d 5h	2d 18h	22,1%	23,5%
21-08-19	7d 19h	1d 16h	21,4%	11d 17h	3d 7h	28,1%	24,8%
Average	**-**	**-**	**5,8%**	**-**	**-**	**13,1%**	**9,5%**

Table 26: Standstill of degassing rooms first two orders locked steepest hill climbing

	Degassing room 1			Degassing room 2			Total		
Situation	S	L	D	S	L	D	S	L	D
17-07-19	0,0%	0,0%	0,0%	10,1%	0,0%	-10,1%	5,1%	0,0%	-5,1%
24-07-19	0,0%	0,0%	0,0%	16,9%	10,6%	-6,3%	8,5%	5,3%	-3,2%
26-07-19	2,2%	0,0%	-2,2%	22,3%	0,0%	-22,3%	12,3%	0,0%	-12,3%
30-07-19	0,0%	0,0%	0,0%	5,4%	9,8%	4,4%	2,7%	4,9%	2,2%
05-08-19	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
07-08-19	0,0%	0,0%	0,0%	27,2%	34,4%	7,2%	13,6%	17,2%	3,6%
16-08-19	58,8%	24,8%	-34,0%	12,1%	22,1%	10%	35,5%	23,5%	-12,0%
21-08-19	39,3%	21,4%	-17,3%	30,6%	28,1%	-2,5%	35,0%	24,8%	-10,2%
Average	**12,5%**	**5,8%**	**-6,7%**	**15.6%**	**13,1%**	**-2,5%**	**14.1%**	**9,5%**	**-4,6%**

Table 27: Comparison standstill of degassing rooms, steepest hill climbing and first two orders locked

5.5 Summary

The answer our last sub-question 'What are the effects of specific conditions?' we make comparisons. During the results in sections 5.2, 5.3 and 5.4 we already made some comparisons. Now that we have the results from all specific conditions we can compare these with each other. The figures for these comparisons can be found below.

Figure 9 displays the throughput averages by the conceptual model and steepest hill climbing. It is clear to see that the implementation of the heuristic improves the throughput averages, regardless of the conditions. By percentage, the throughput improved the most in the normal situation.

As we discussed for comparing latenesses, the number of products late per total number of products gives the best indication if the situation is getting worse or better. We can see from the comparison tables that these are all quite similar.

Figure 10 shows the standstill averages from the conceptual model, steepest hill climbing and steepest hill climbing with the first two orders locked. We can see that the proportion is in each situation relatively the same, meaning the first degassing rooms has less standstill than the second degassing room. This is due to the priority in the code that is earlier mentioned.

We also compare the throughput averages with the standstill averages in Figure 11. From that, we can see that on average, whenever the throughput is higher, the average standstill of degassing rooms is higher too. Based on the total time that is on average the same or longer with steepest hill climbing, differences lie within the combination of products in the degassing rooms and the last couple of products that are not assigned to a degassing room. Because we deal with a schedule that finishes at an specific moment, and the reality that is continouous, we can have products that do not going in a degassing room in our schedule but possibly in reality they do. For this, we make a recommendation in 7.2.

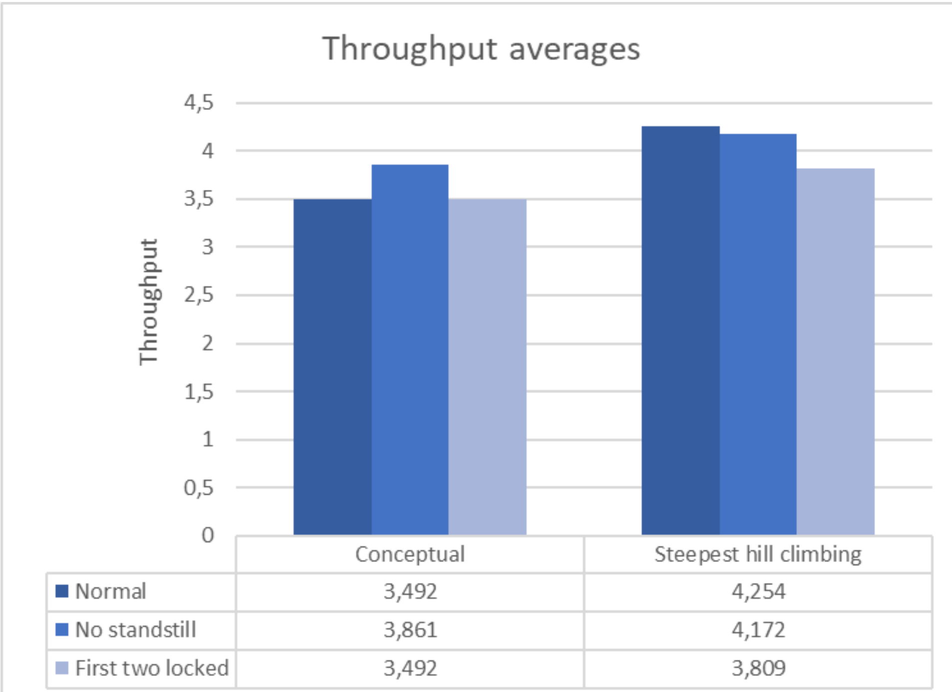

Figure 9: Throughput averages of the normal situation and experiment situations

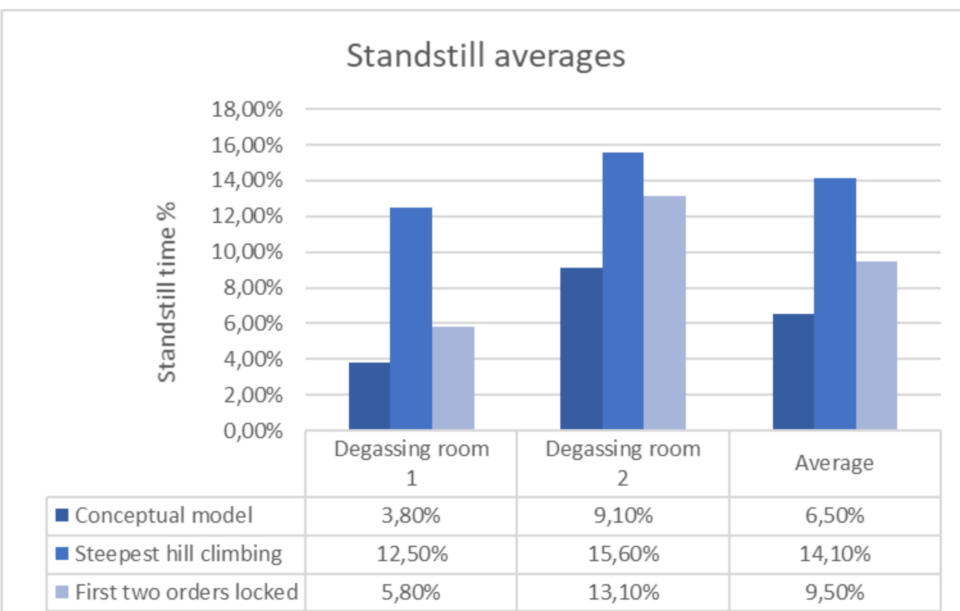

Figure 10: Standstill averages of the normal situation and experiment situations

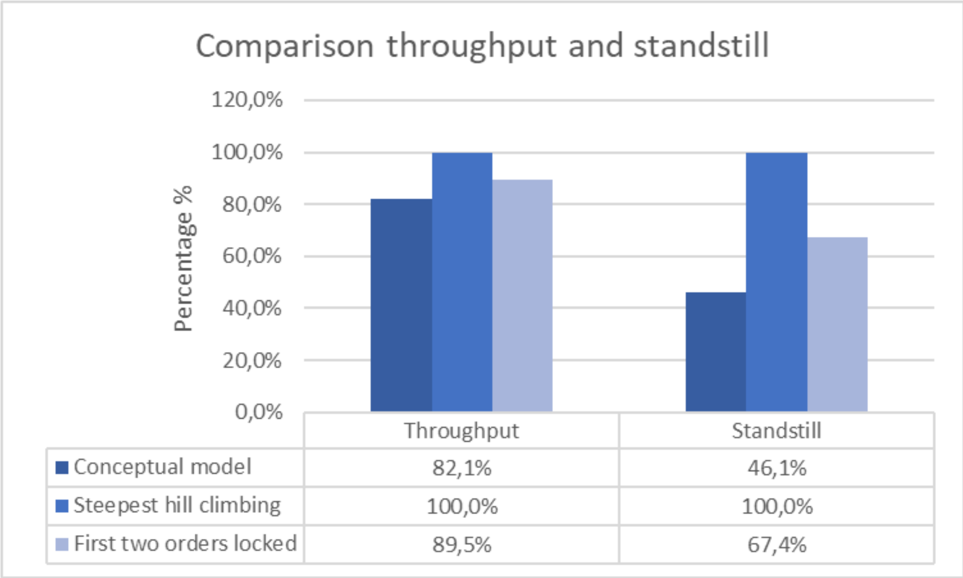

Figure 11: Comparison throughput averages and standstill averages

6 Guideline to maintaining results

This chapter answers our last research question and serves as a guideline for the user of the Excel tool. We divide this chapter into two parts, for maintaining the Excel file (6.1) and maintaining the results (6.2).

6.1 Excel file

Changes in an Excel file are easily made and sometimes unintentional. If a user is not aware of the code in VBA that lies underneath, errors can arise and the whole tool can become inoperable. We classify the parts of the tool as fixed or as unfixed, meaning that for an unexperienced user the fixed parts should remain untouched for it to work properly. Nevertheless, we strongly advise to always have a back-up file of the working tool, should there be any negative changes that cannot be explained by the user.

6.1.1 Fixed parts

The VBA code refers to columns for the information that they contain or for the destination the information has to flow to. Should a column be switched or added, then it is most likely that information gets in the wrong places. It can also mean that some information is not taken into account anymore, which can have its consequences for the schedule outcome. We can state that all columns should be fixed, independent of their sheet.

As same as with the columns, row headers are part of the layout and should remain fixed. The code considers the number of rows in which no useful information is positioned or will be placed. By changing this, products can be missed in the calculations or the whole layout can be overwritten.

The sheets ‘Temporary Copy’ and ‘Initial Copy’ have their purpose on the schedule, as described in section 4.1.2. Although these sheets may seem unnecessary, they should not be removed as this will have major consequences on the outcome of the heuristic.

A last small fixed part is the names the sheets are given. The code refers to these names, so by changing it the code cannot find the sheets with the needed information anymore.

6.1.2 Unfixed parts

When a download from the database with Exsion has been made, all information that is placed in the sheets ‘CDCC’ and ‘Degassing’ can be modified. Some information has an effect on the outcome when changed, but most of the information are just strings of letters and words. So should the reality differ a bit from the database information, it can still be modified. In short, the information that is not part of the layout is unfixed.

In the sheet ‘CDCC’ column A gives the user the option to lock the product in its position. Thus, the intention of this column is to be unfixed. The same holds for the column G in the sheet ‘Degassing’, where the user can assign a product to a degassing room. In doing so, the user should also specify the number of hours since the degassing room began its process in column J.

The last unfixed part are the values of the parameters in the sheet ‘Parameters’. These have their purpose to be unfixed, so that the situation and the code can be changed quite easily.

6.2 Results

6.2.1 Normal situation

As it is described in section 4.1.2, a schedule can be obtained by clicking the button 'Conceptual' or 'Heuristic'. Both give their associated answers to which the user can draw its results. Clicking the button also results in a pop-up screen, giving the end time of the schedule. If the user takes this time and subtracts the time of which the download is made, the total production time is calculated. To get the throughput, the number of products need to be divided by this production time.

In the sheet 'Due Date', all the vital information for calculating the values as it is done in chapter 5 can be found. By making use of the standard Excel functions, averages and sums can be calculated.

Standstill of degassing rooms can be measured by hand. When looking at the schedule, the user can see when a degassing room is not in use during the production time.

6.2.2 No standstill of degassing rooms

For calculating the same results as the normal situation, a different Excel file is needed. To implement the rule of no standstill, some parts of the codes need to be altered. It is safer to use this Excel file when this rule needs to be taken into account.

6.2.3 First two orders locked

As the title of the experiment explains, the first two orders of the CDCC production plan need to stay in the same position. This can be done by locking the first two orders in the sheet 'CDCC' in column A.

7 Conclusions and recommendations

7.1 Conclusions

The goal of this research is set by the main question and is reached because we have acquired an answer to this question. We describe our conclusions according to the order of the sub-questions. First we summarize our conclusions per chapter until we reach chapter 5, which we discuss more broadly. For better readability, we repeat our main question:

“How to gain a higher throughput of medium voltage cables at the insulating and degassing stages?

From expressing the production line within our scope in chapter 2, we stated that the CDCC can be seen as a constant possible bottleneck. This leads to the conclusion that we see the rest of the production line, after our scope, saturated. Note that this is under the condition that should the situation shift away from average, the expertise of TKF is still required to review this conclusion. For the wire drawing step, constant tuning between schedules is needed for it to work at the CDCC.

In our theoretical chapter, chapter 3, we reviewed 5 different frameworks to express our production line. We concluded on 5 important criteria that it is best to express our production line through a custom made algorithm in Microsoft Excel. Simultaneously we reviewed the obvious accompanying solving methods. Having concluded to create a custom algorithm, a heuristic was the best choice for solving and optimization purposes. To our situation, steepest hill climbing is sufficient and leads us to a local minimum or maximum.

Chapter 5 displayed the results of the calculations of 8 different scenarios. We first discuss the results per KPI and end with conclusions about the experiments.

When we look at the throughput, we can conclude that steepest hill climbing improves it in all scenarios compared to the conceptual model, but changes with the given conditions. The condition which allows no standstill of the degassing rooms also gave a significant improvement for the conceptual model. In some cases this leads to an incomplete degassing room at the end of the schedule, but this probably will not be the case when implemented because in reality new products will arrive for which we could not make a schedule.

The lateness in delivery has made no substantial change when applying the heuristic or the different conditions. Because we do not aim to minimize in our code the number of products that are delivered too late, improvement was not shown. We conclude that most products are already expected to be delivered late, especially for the products that have a higher priority assigned by TKF. This can be seen in section 5.1.2. Those that have a low priority have sometimes more than a month until the set delivery date, which gives a lot of space to delay the production of this product and still not be delivered too late.

We can see that steepest hill climbing finds solutions that on average have a higher standstill time per degassing room. At first, this may be counterintuitive but can be explained by the combinations that go into the degassing rooms. A set of products that all have the same degassing time can be worth the wait over a set of products with different degassing times.

When looking at the experiments, 'no standstill in degassing rooms' proved an interesting insight with regard to the throughput. On average it can be beneficial not to wait at products to complete the degassing room. Even when steepest hill climbing is not used, it can be worth applying this rule.

The experiment 'first two orders locked' represents a more realistic schedule but due to the fact that there are two orders less to swap, steepest hill climbing has fewer schedules to compare. This leads on average to lower throughput.

7.2 Recommendations

Based on the results in chapter 5, we recommend creating schedules with steepest hill climbing and the first two orders locked. This is closest to reality and gives a local optimal schedule.

The 'no standstill of degassing rooms' policy promises interesting results too but can be hard to implement because it is counterintuitive. It may take some time to convince employees that this would, in the end, lead to a higher throughput. Therefore we recommend running more situations with this policy, in order to get more stable statistics.

Overall when creating schedules, we recommend trying to approach a continuous situation. The reality is continuous and the schedule is not, so the end of the schedule can be up for discussion. To approach a more continuous situation, it is important to find the right moment on which you leave the old schedule behind and create a new one. This, of course, would not be at the end of the schedule. Ideally, the user takes the planning for the degassing rooms and considers a new schedule whenever a degassing room has no more products scheduled. By doing so, the products that otherwise would be scheduled to degas without a degassing room, can be scheduled to a degassing room with new products obtained from a later situation.

7.3 Further research

For approaching a continuous situation, we could expand the list of products that are in line at the CDCC. With the current system settings this is not possible, but there are ways to pass products to the next step.

For the optimal point to where a schedule should be followed or where a new one should be created, additional research can be done. This will enhance the statistics about throughput which can be beneficial when making a trade-off.

In the created Excel tool, the lateness is not the objective function that needs to be minimized. If TKF decides to optimize the throughput and take the number of products that are late in regard, the code in VBA should be changed. This possibly will improve the lateness.

We used steepest hill climbing to find a local minimal makespan, but there are other ways that can also find a global minimum. Consider simulated annealing when continuing with heuristics.

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Appendix A: Overview of lost hours week 5, 2019

	27-jan	28-jan	29-jan	30-jan	31-jan	1-feb	2-feb	3-feb	**Totaal**
	zo	ma	di	wo	do	vr	za	zo	
EI MANTELLIJN 1	0	18	9	-13	12	19	0	0	**44**
EI MANTELLIJN 2	0	4	7	5	12	12	0	0	**40**
EI MANTELLIJN 3	0	12	6	15	14	55	0	0	**103**
EI CDCC	0	32	22	-5	9	41	0	0	**100**
EI ISOLATIELIJN 1	0	-6	1	-4	2	1	0	0	**-6**
EI ISOLATIELIJN 2	0	5	-3	-1	5	-5	0	0	**1**
EI RUBBERLIJN 1	0	-5	10	1	-3	8	0	0	**10**
EI DRUMTWISTER 1	0	7	-3	10	14	4	0	0	**31**
EI DRUMTWISTER 2	0	8	15	11	7	10	0	0	**51**
EI SCHERMLIJN 1	0	-1	4	5	-3	6	0	0	**12**
EI SCHERMLIJN 2	0	0	0	0	0	0	0	0	**0**
EI SCHERMLIJN 3	0	-3	2	0	0	0	0	0	**-1**
EI SCHERMLIJN 4	0	8	0	0	6	8	0	0	**22**
EI CONFORM LIJN	0	13	5	10	-1	7	0	0	**33**
EI LOODEXTRUDER	0	0	7	3	2	0	0	0	**11**
EI VLECHTER 48-1	0	-3	11	-3	8	0	0	0	**13**
EI WIKKELLIJN 1	0	8	-21	-12	1	8	0	0	**-15**
Totaal	**0**	**97**	**71**	**21**	**84**	**174**	**0**	**0**	**448**

Appendix B: Layout conceptual model

	A	B	C	D	E	F	G	H	I	J	K	L	M
1						Currently at CDCC							
2	Free/Locked	Product order number	Article description 1	Article description 2	End product description 1	End product description 2	Length	Processing time	Setup time	Priority	Value	Delivery date end product	Order
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													
13													
14													
15													
16													
17													
18													
19													
20													
21													
22													
23													
24													
25													

Figure 12: First 25 rows of conceptual model, CDCC sheet

	A	B	C	D	E	F	G	H	I	J
1				Currently degassing					Hours since begin degassing room 1	
2	Product order number	Article description 1	Article description 2	End product description 1	End product description 2	Value	Which degassing room?		Hours since begin degassing room 2	
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										
21										
22										
23										
24										
25										

Figure 13: First 25 rows of conceptual model, degassing sheet

Conceptual

Heuristic

CDCC						
Product number	Article description 1	Article description 2	End product description 1	End product description 2	Start time production	Finish time production

Degassing room 1					
Product number	Article description 1	Article description 2	End product description 1	End product description 2	Start time degassing

Figure 15: First 25 rows of conceptual model, schedule sheet part 1

Degassing room 2					
Product number	Article description 1	Article description 2	End product description 1	End product description 2	Start time degassing

No degassing room						
Product number	Article description 1	Article description 2	End product description 1	End product description 2	Start time degassing	Finish time degassing

Figure 14: First 25 rows of conceptual model, schedule sheet part 2

Appendix C: Exsion queries

	A	B	C	D	E	F	G	H
1	PO_BEW._PLANREGEL	'CDCC'!$B$3:$B$32		10-7-2019 14:09				7.0
2	Connectie	1						
3	Tabel	99000792	80020	50050	50055			
4	JOINTYPE	1	1	1	1	FILTER	VERBERG	SORTEREN
5	Status vorige bew.	80310				3	WAAR	
6	Nr.	8				*EI CDCC*	WAAR	
7	Afdelingnr.	9				*ENERGIE*	WAAR	
8	Prod.ordernr.	75	2				WAAR	
9	Prod.nr.		10				ONWAAR	
10	Artikelomschrijving 1	80080					ONWAAR	
11	Artikelomschrijving 2	80081					ONWAAR	
12	Eindproduct Omschrijving	80090					ONWAAR	
13	Eindproduct Omschrijving2	80091					ONWAAR	
14	Gereed	80084				Nee	WAAR	
15	Lengte		16			>200	ONWAAR	
16	Inputaantal	77					WAAR	
17	Bewerkingstijd	13					ONWAAR	
18	Insteltijd	12					ONWAAR	
19	Lengte (Werkelijk)		18				WAAR	
20	Bewerkingsplaats		33			*EI CDCC*	WAAR	
21	Prioriteit	80066					ONWAAR	-1
22	Variant	80004		51			WAAR	
23	Artikelnr.	80079		50			WAAR	
24	Configuratie code			1	1		WAAR	
25	Waarde				53	>=50	ONWAAR	
26	Parameterkoppelingcode				15	DROGEN_ZWETEN	WAAR	
27	Omschrijving				52	Tijdsduur	WAAR	
28	Status			20		<>Afgesloten	WAAR	
29	Leverdatum eindproduct	80092					ONWAAR	2

Figure 16: Exsion query for CDCC results

P	Q	R	S	T	U	V	W
PO_BEW.	'Degassing'!$A$3:$/	10-7-2019 14:09					7.0
Connectie	1						
Tabel	99000792	80020	50050	50055			
JOINTYPE	1	1	1	1	FILTER	VERBERG	SORTEREN
Status vori	80310				3	WAAR	
Nr.	8				*EI VERW/	WAAR	
Afdelingnr	9				*ENERGIE	WAAR	
Prod.orde	75	2				WAAR	
Prod.nr.		10				ONWAAR	
Artikeloms	80080					ONWAAR	
Artikeloms	80081					ONWAAR	
Eindprodu	80090					ONWAAR	
Eindprodu	80091					ONWAAR	
Gereed	80084				Nee	WAAR	
Variant	80004		51			WAAR	
Artikelnr.	80079		50			WAAR	
Configuratie code			1	1		WAAR	
Waarde				53	>=50	ONWAAR	
Parameterkoppelingcode				15		WAAR	
Omschrijving				52	Tijdsduur	WAAR	
Status			20		<>Afgeslot	WAAR	
Connectie	-2					WAAR	
Bewerkingsplaats		33			*EI VERW/	WAAR	

Figure 17: Exsion query for degassing results

Appendix D: Flowcharts conceptual model

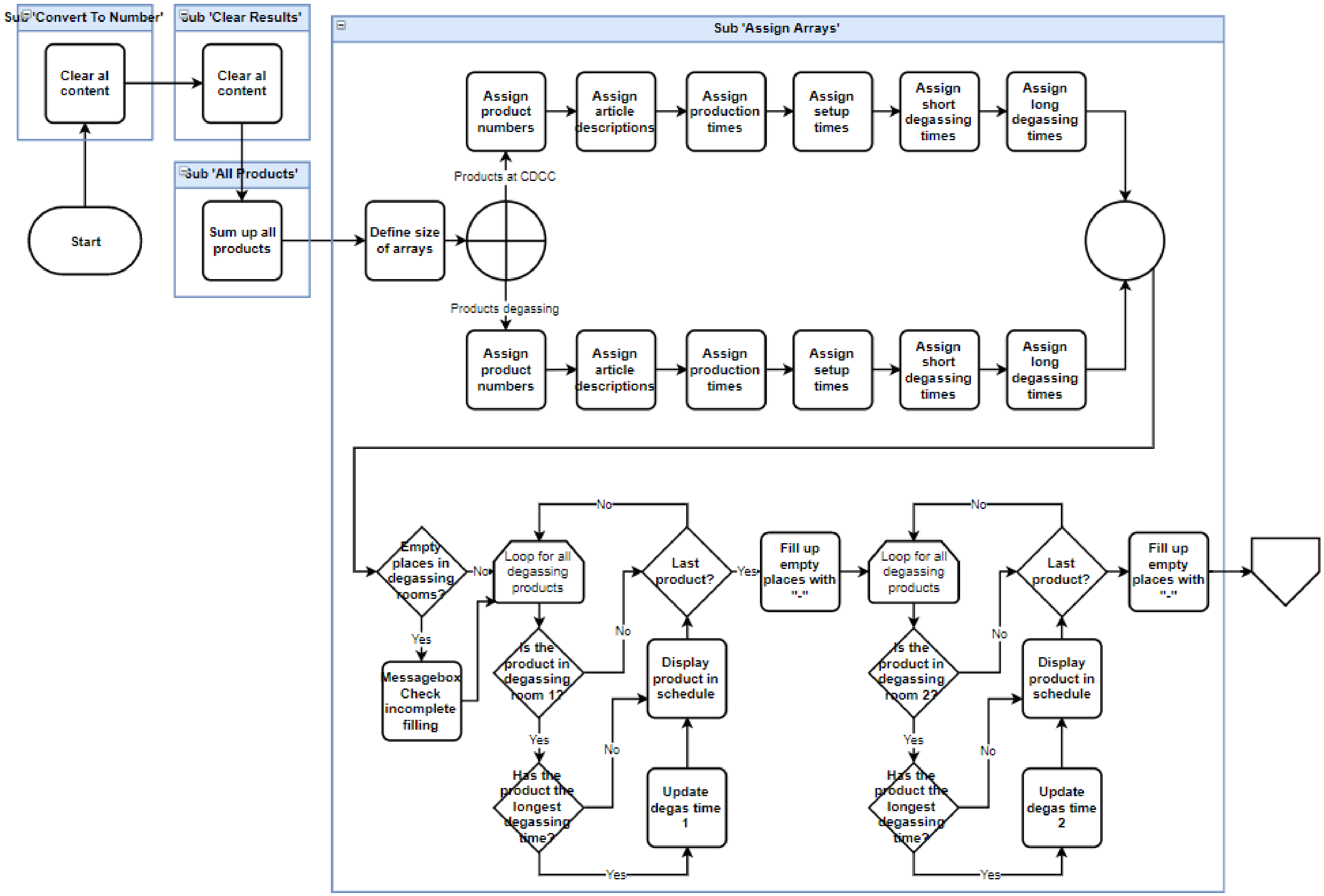

Figure 18: Flowcharts Sub "Convert To Number", "Clear Results", "All Products" and "Assign Arrays"

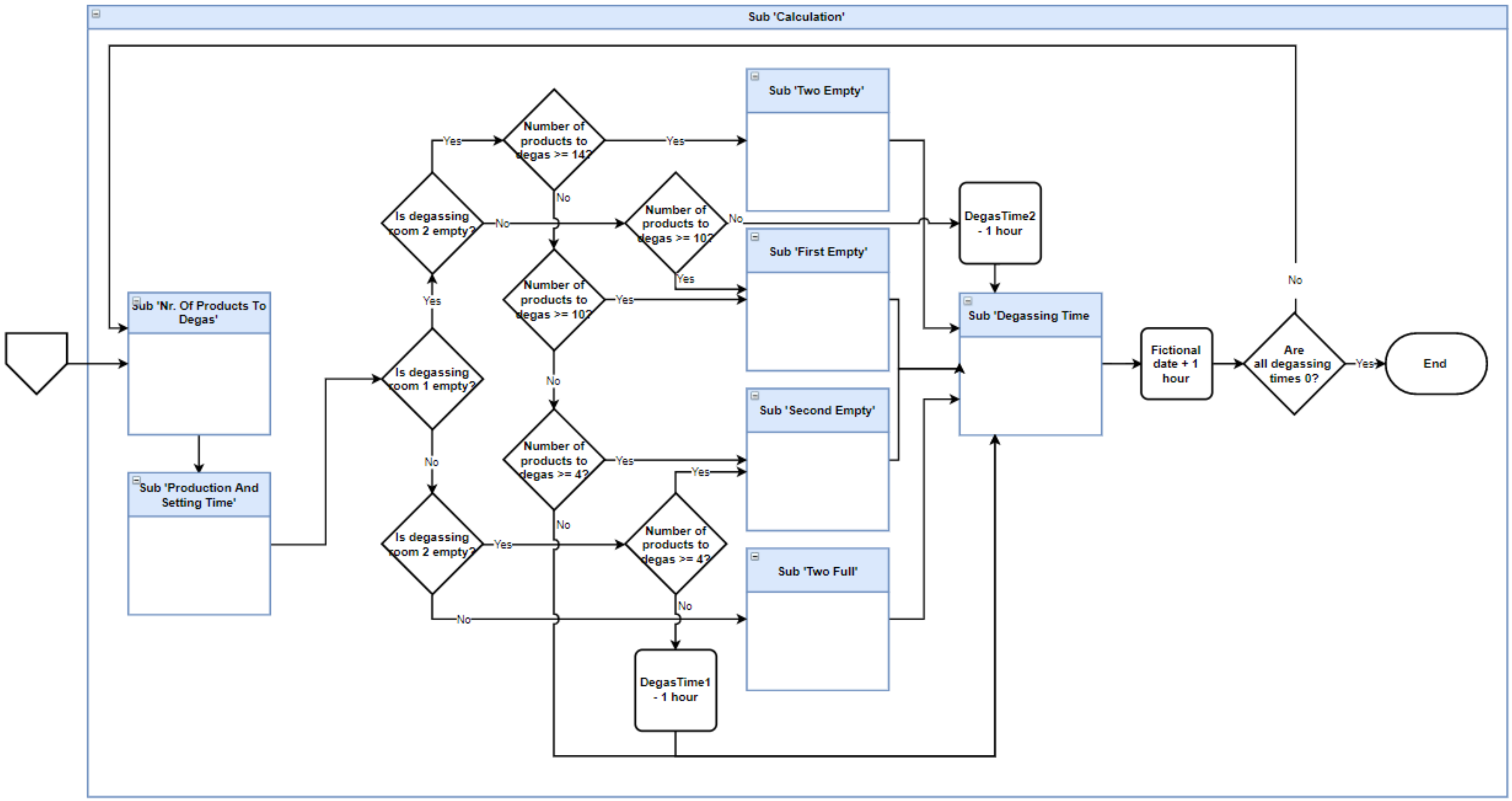

Figure 19: Flowchart Sub "Calculation"

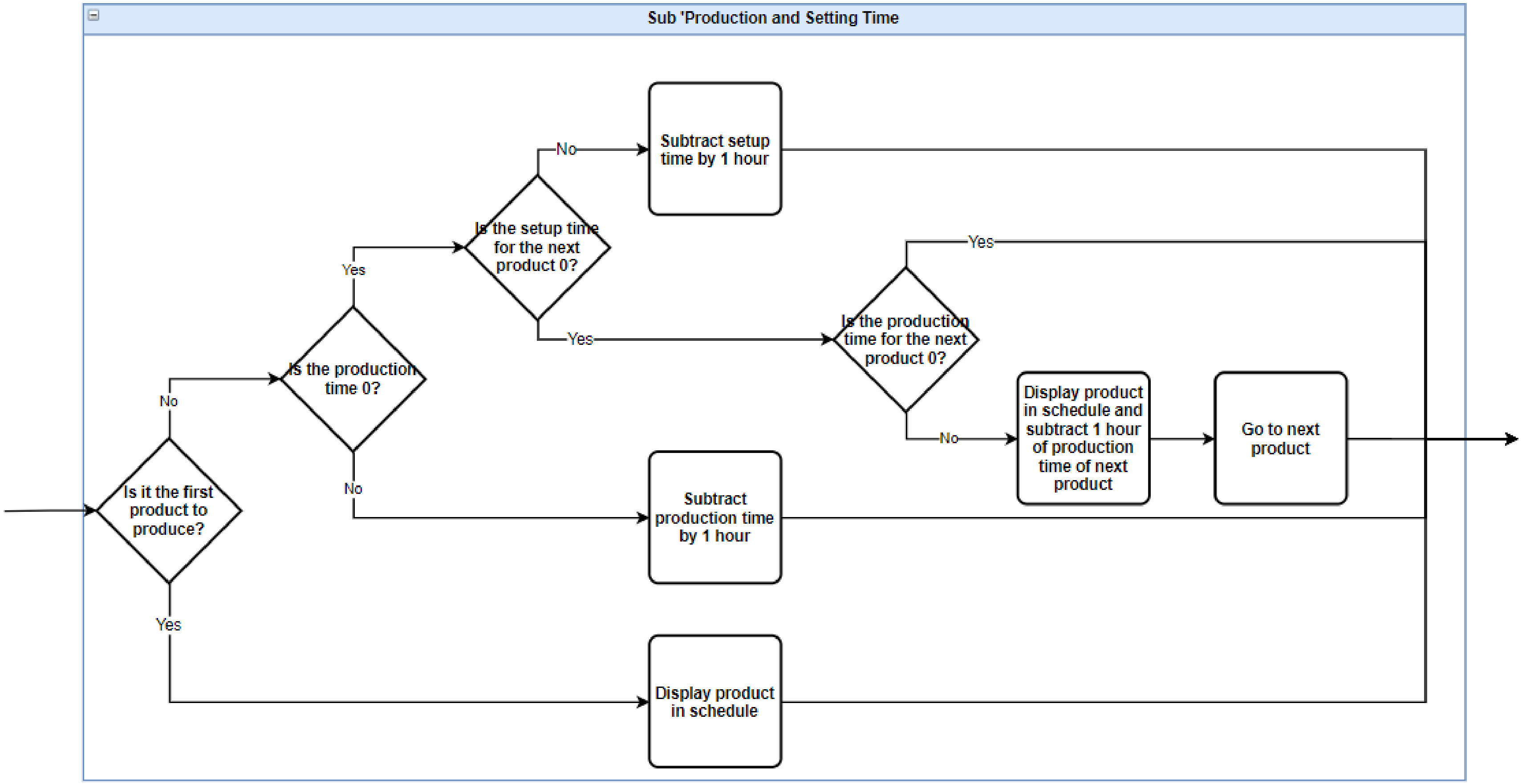

Figure 20: Flowchart Sub "Production and Setting Time"

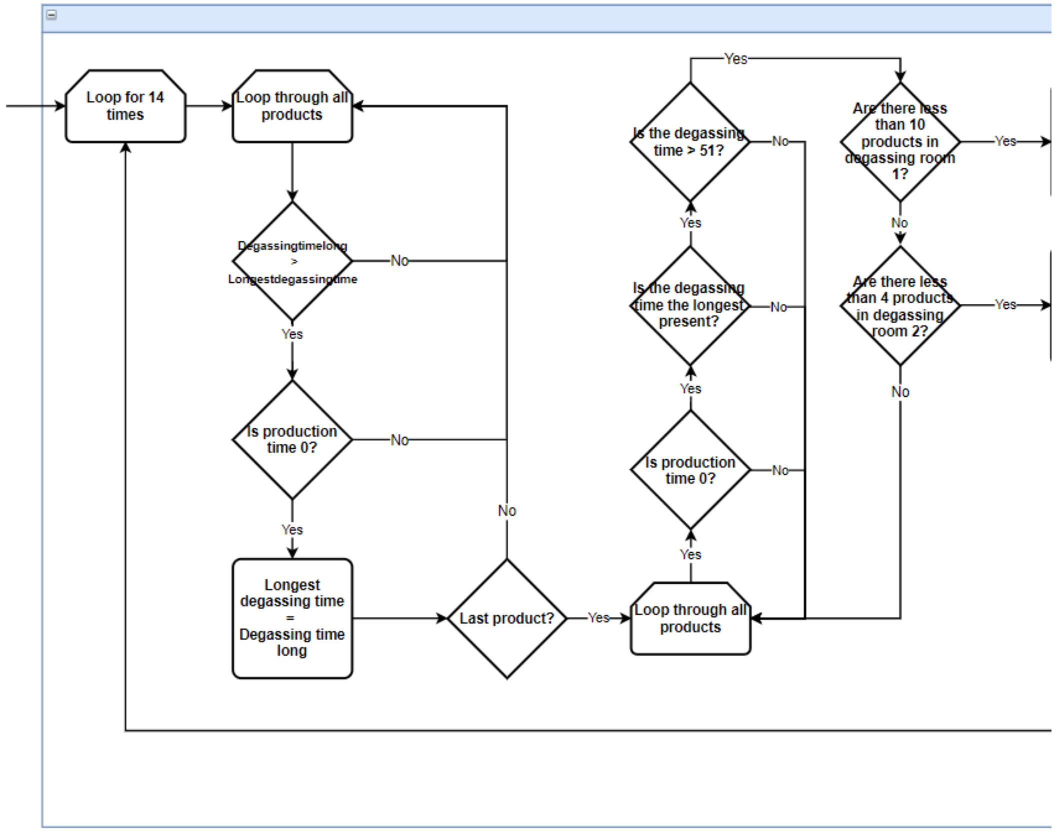

Figure 21: Left side of flowchart Sub "Two Empty"

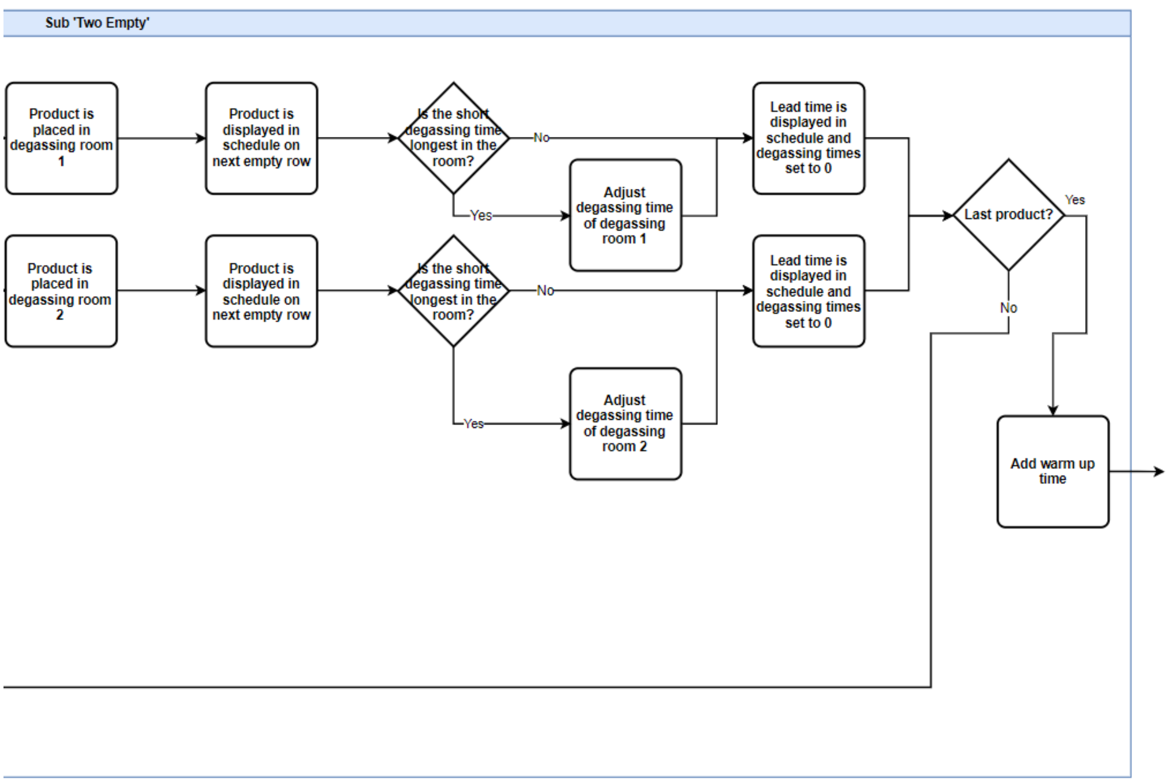

Figure 22: Right side of flowchart Sub "Two Empty"

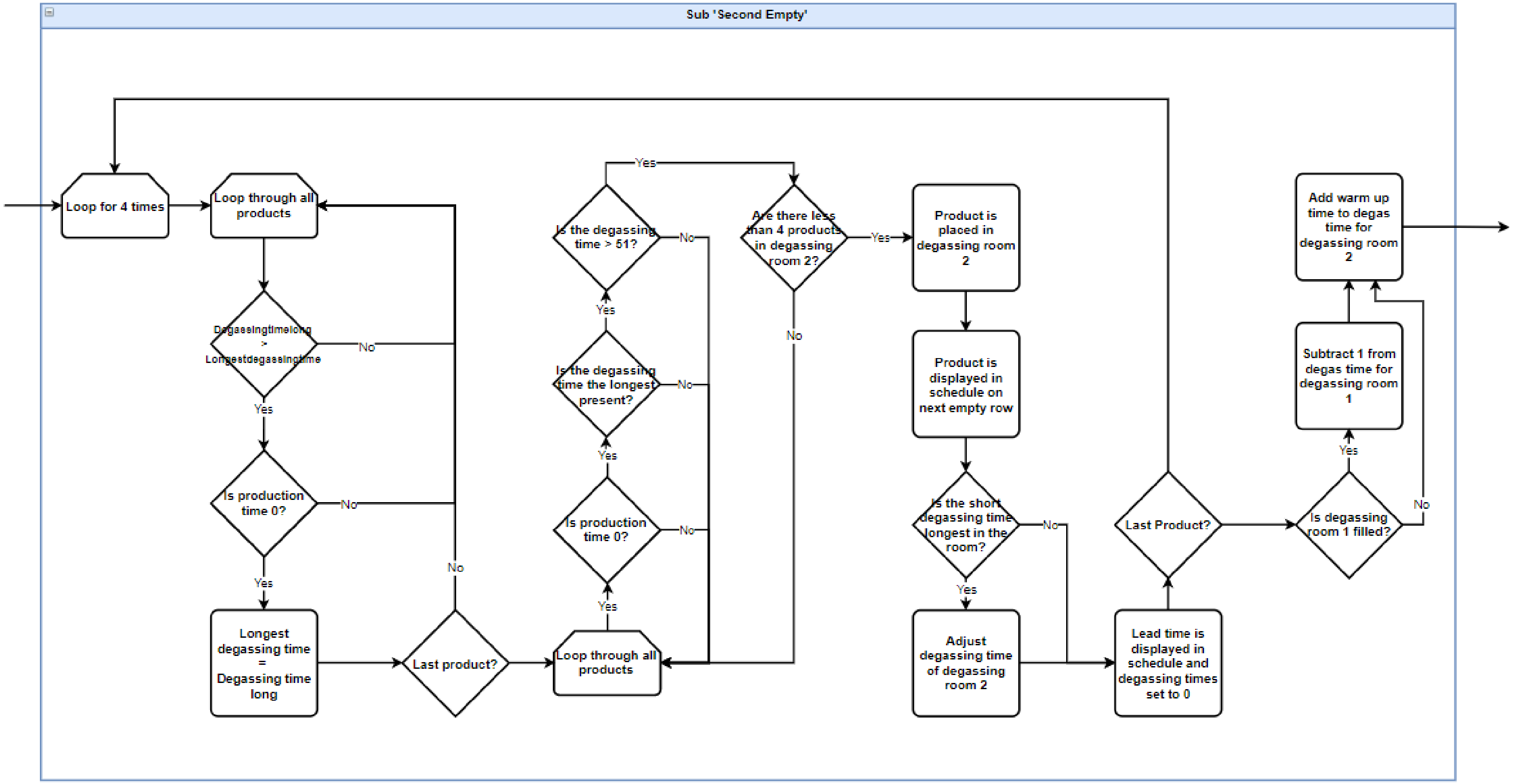

Figure 23: Flowchart Sub "Second Empty"

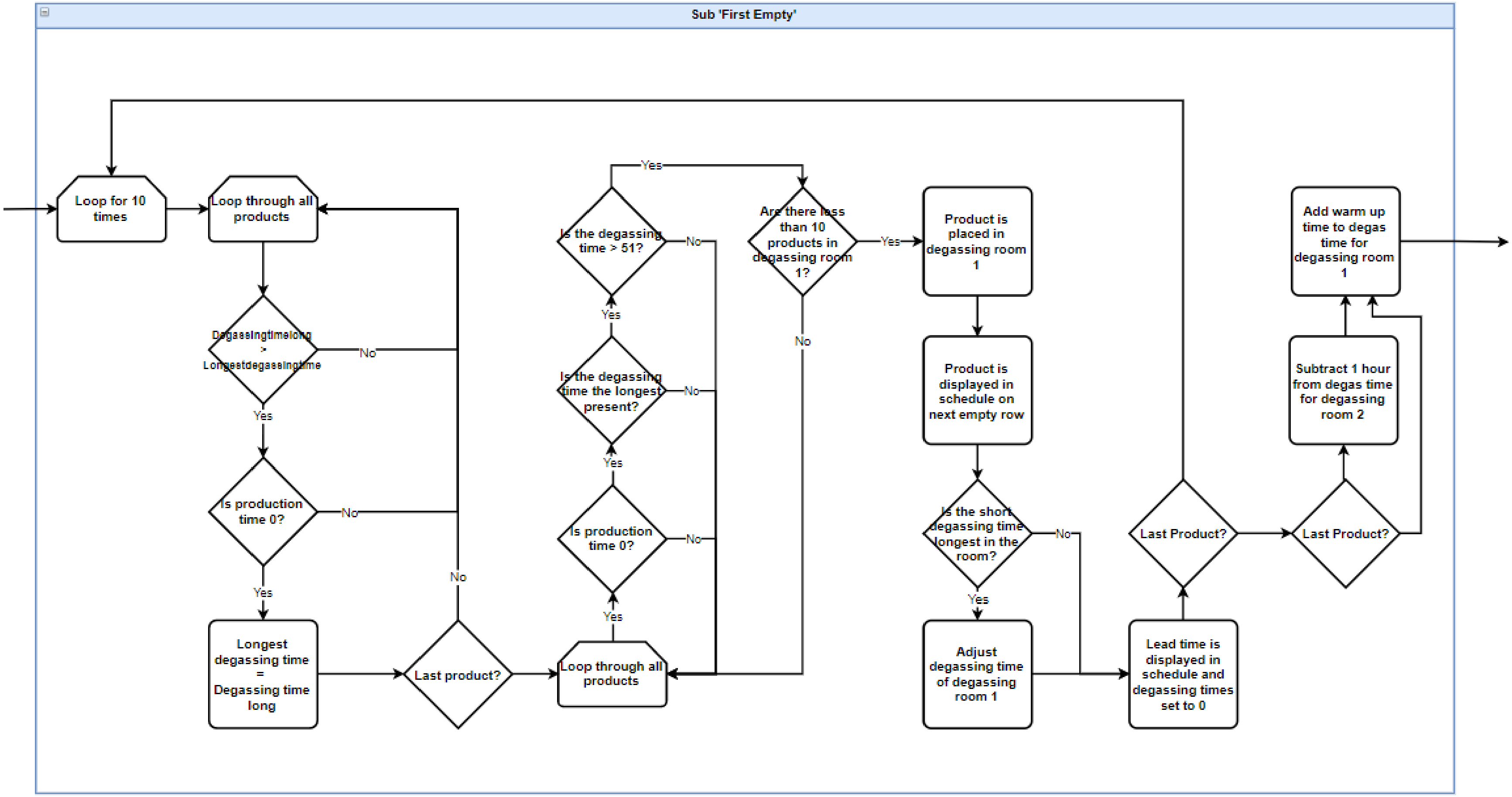

Figure 24: Flowchart Sub "First Empty"

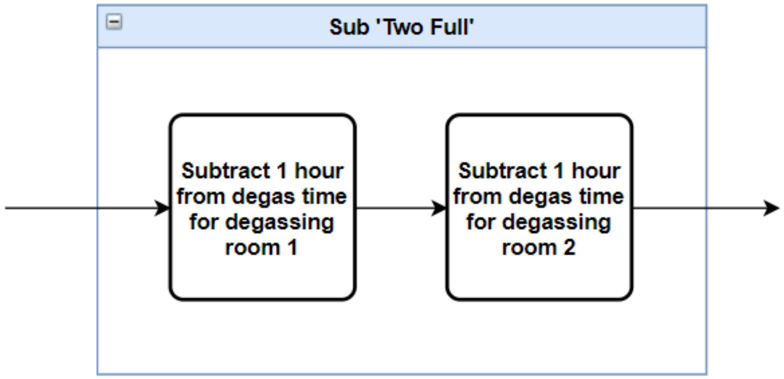

Figure 25: Flowchart Sub "Two Full"

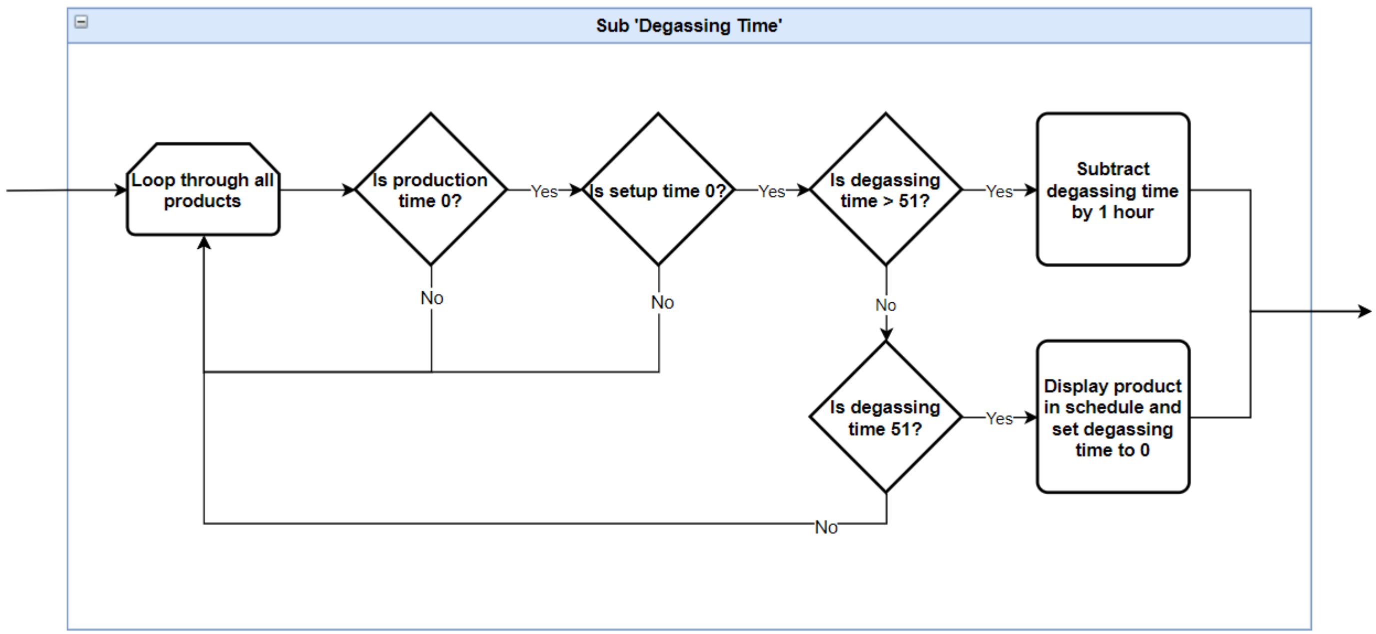

Figure 26: Flowchart Sub "Degassing Time"

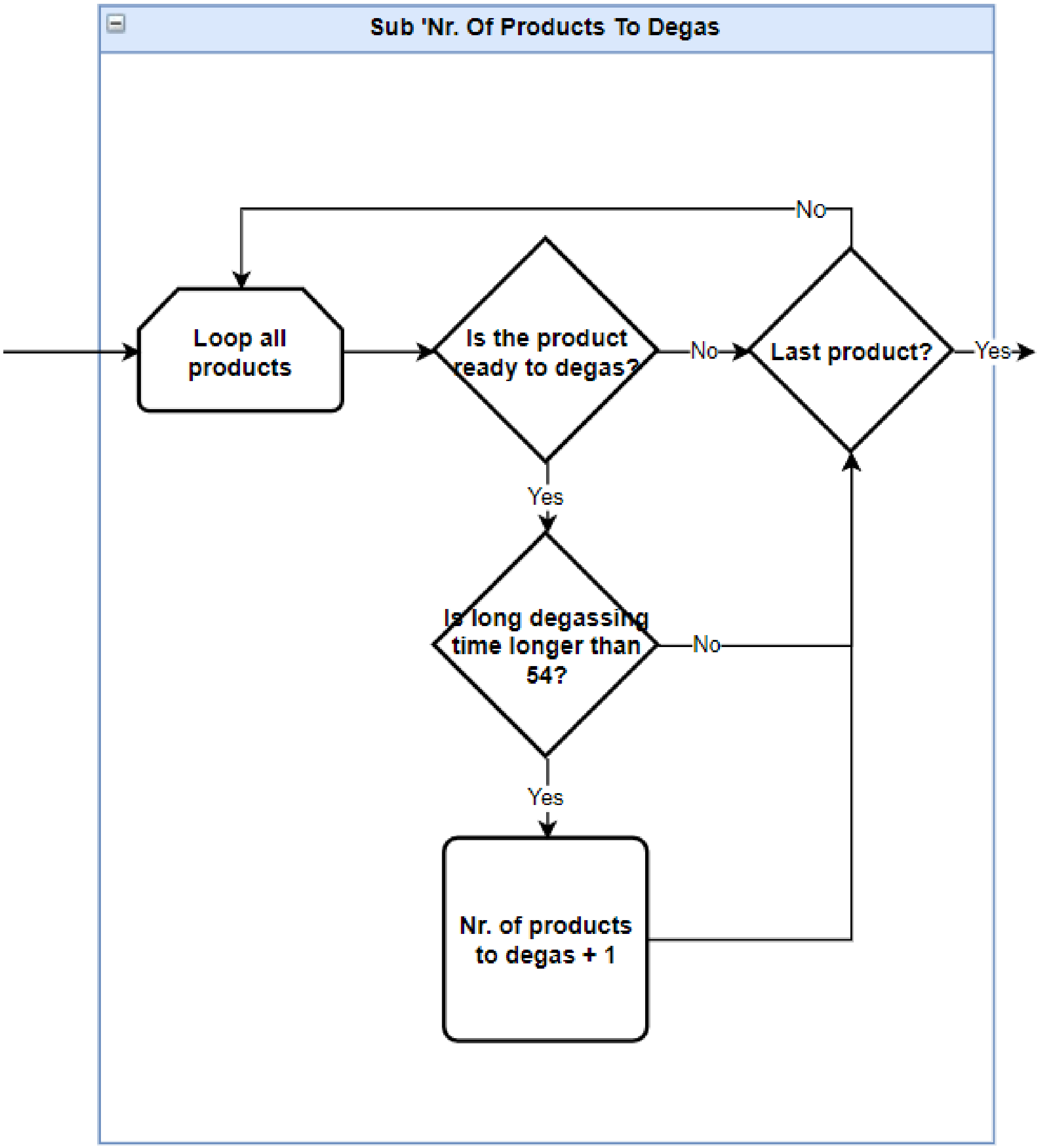

Figure 27: Flowchart Sub "Nr. Of Products To Degas"

Appendix E: Flowcharts steepest hill climbing

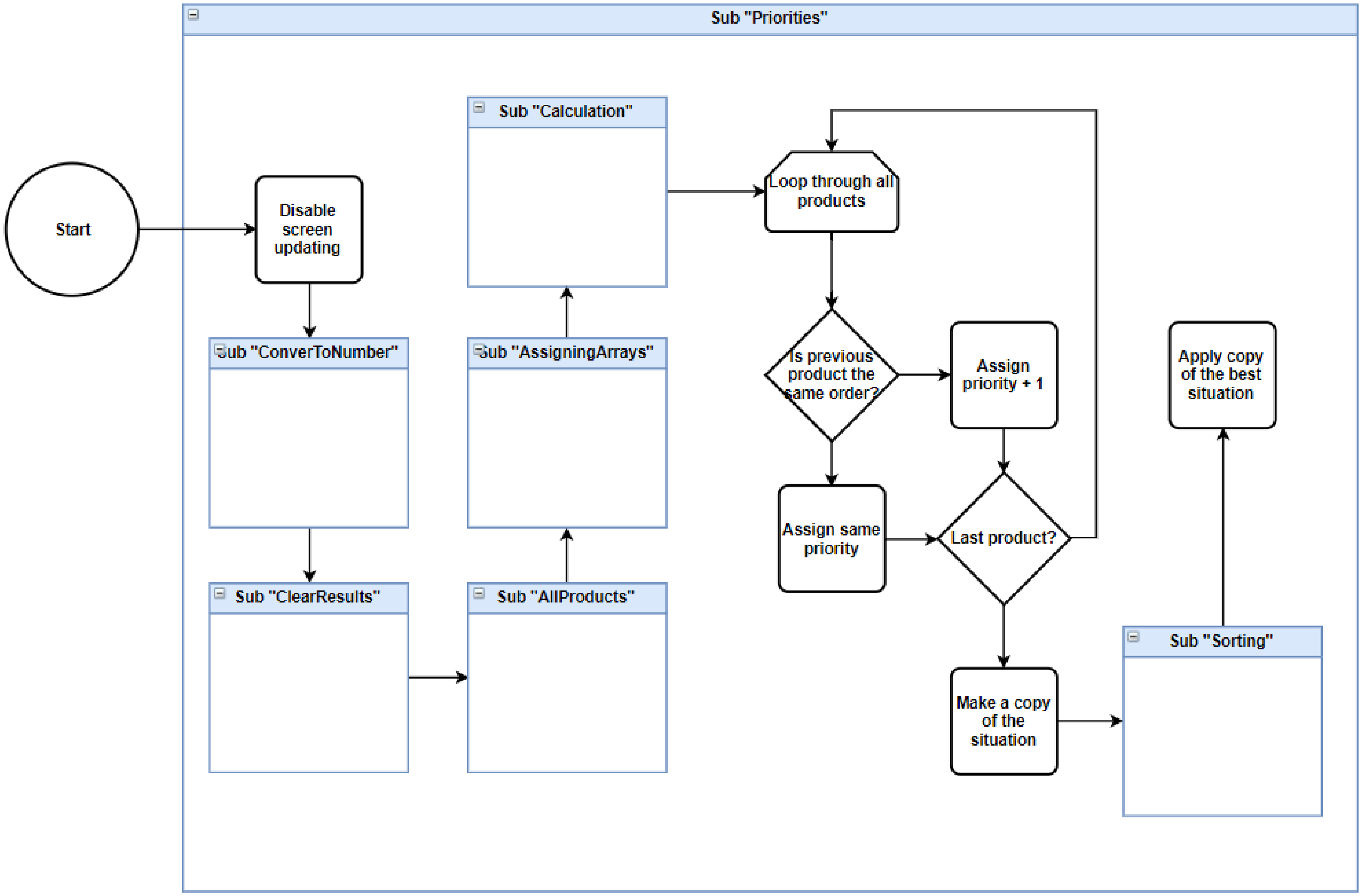

Figure 28: Flowchart Sub "Priorities"

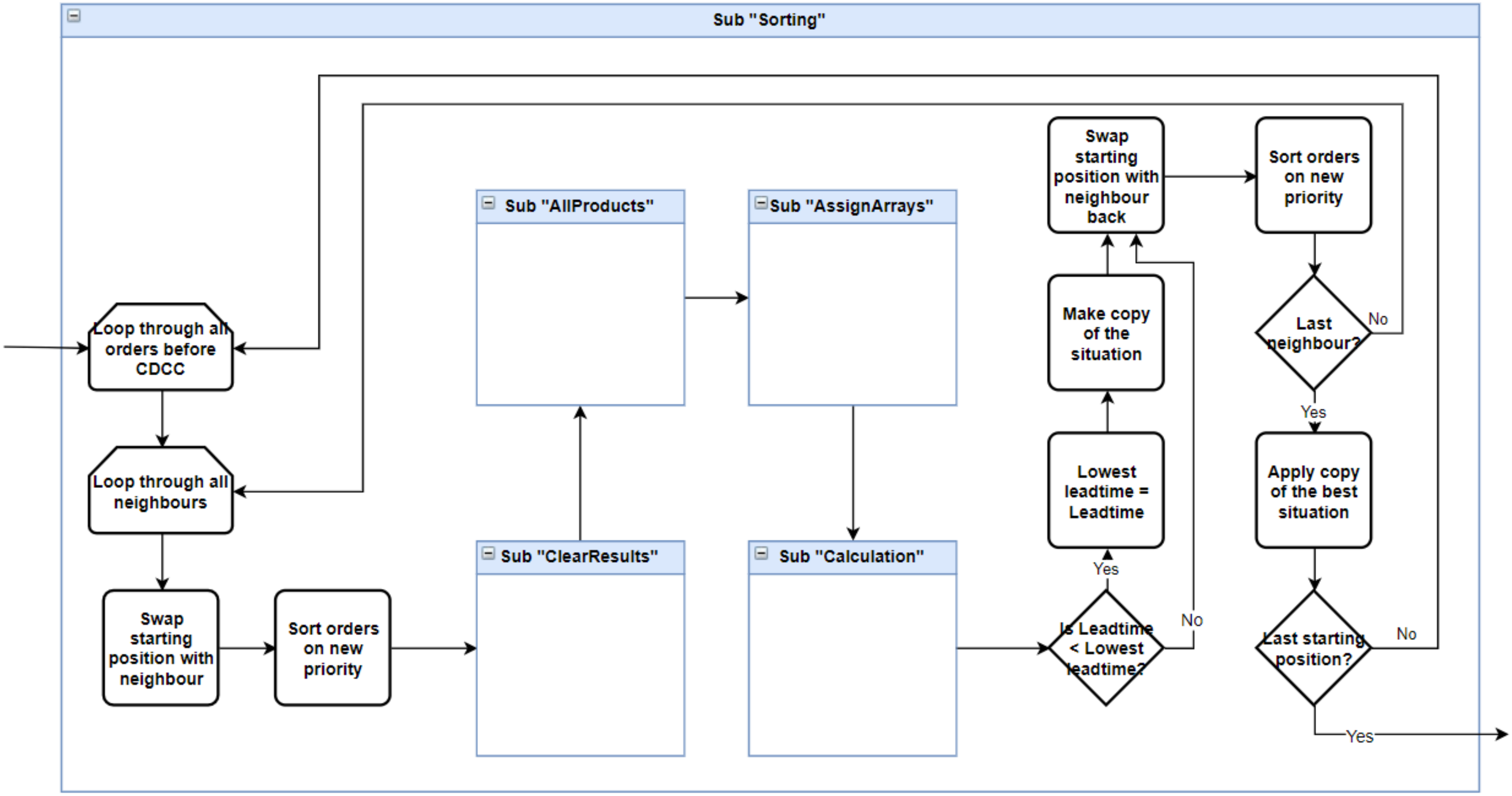

Figure 29: Flowchart Sub "Sorting"

Appendix F: Comparison total run times

	Degassing room 1			Degassing room 2			Total		
Situation	**C**	**S**	**D**	**C**	**S**	**D**	**C**	**S**	**D**
17-07-19	5d 23h	9d 11h	3d 12h	9d 11h	6d 15h	-2d 20h	15d 10h	16d 2h	0d 16h
24-07-19	5d 23h	5d 23h	0d 0h	6d 16h	7d 4h	0d 12h	12d 15h	13d 3h	0d 12h
26-07-19	9d 11h	9d 16h	0d 5h	5d 23h	7d 16h	1d 17h	15d 10h	17d 8h	1d 22h
30-07-19	2d 11h	2d 11h	0d 0h	7d 6h	11d 16h	4d 10h	9d 17h	14d 3h	4d 10h
05-08-19	3d 1h	3d 1h	0d 0h	5d 23h	5d 23h	0d 0h	9d 0h	9d 0h	0d 0h
07-08-19	3d 1h	3d 1h	0d 0h	3d 18h	3d 9h	-0d 9h	6d 19h	6d 10h	-0d 9h
16-08-19	8d 14h	12d 1h	3d 11h	11d 14h	10d 16h	-0d 22h	20d 4h	22d 17h	2d 13h
21-08-19	3d 21h	9d 18h	5d 21h	12d 23h	10d 18h	-2d 5h	16d 20h	20d 12h	3d 16h

Table 28: Comparison total times of conceptual and steepest hill climbing