MASTER

A decision support tool for getting maximum value from a limited maintenance budget

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Master thesis project
Maintenance Vlisco

A decision support tool for getting maximum value from a limited maintenance budget.

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Preface

This report is the result of my graduation project for the master program Operations Management and Logistics at the Eindhoven University of Technology. The project was carried out at Vlisco Netherlands B.V in Helmond. Despite some ups and downs, I really enjoyed working on this project, it has been a very challenging experience.

First, I would like to thank my first supervisor S.D.P. Flapper, for guiding me through the project. I thank him for all the time he put into my research project. His critical but always very constructive feedback and the many meetings we had to discuss my research project, really helped me a lot. When I got stuck and had problems during my project, Flapper could see the problems in a different way, which helped me solving these problems. I also would like to thank my second supervisor H. Peng, for her time and some critical remarks which helped me improving my final report.

Next, I would like to thank Ton Huibers for the opportunity to perform my master thesis at his department. I want to thank him for all the time he spent on guiding me and the good discussions we had about my project. I know time did not always come as easy, having a very busy agenda as the maintenance manager of Vlisco. I also would like to thank Ton for his continued confidence in me even when the project wasn't going as smooth halfway through.

Also thanks to my colleagues at Vlisco. I am amazed about how easy going the people working at this company are. The working environment at Vlisco could be hectic at times, but all around it was very nice.

Finally, I would like to thank my parents and brothers for their continuing support during my entire study. Also thanks to my fellow students and friends, without you guys this whole experience wouldn't have been as fun.

Eric Bolder

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Abstract

When spending its maintenance budget, the maintenance department of Vlisco wants to know on which production facilities it should focus to achieve the best results possible. Maintenance Vlisco is looking for a quantitative way to determine how to spend their maintenance budget by identifying which production facilities need most attention. To answer this question a mixed integer linear programming model is developed to identify the replacements that have to be performed to keep the total maintenance costs at a minimal level. The resulting model provides insights in which replacement to perform on which machine and the implications of a higher or lower maintenance budget.

Management summary

In this report the results of a master thesis project conducted at Vlisco Netherlands B.V. are presented.

Introduction

Vlisco Netherlands B.V., the headquarters of Vlisco, is a manufacturing company in Helmond, in the South of the Netherlands. Vlisco is a fashion company that focuses on the African market. Since 1864 Vlisco has been designing and producing colorful fashion fabrics. The fabrics made by Vlisco play an essential role in the lively west and central African culture. Over the years Vlisco has become a well-known and popular brand. Since 2006, Vlisco strengthens her position as a brand by presenting four new collections each year. Today, Vlisco is a leader in the premium segment and her top quality fabrics are sold in more than 30 African countries. The trademark "guaranteed Dutch wax" that is printed on the edge of the fabrics is proudly worn by the people in Africa.

Problem statement and research questions

The maintenance department of Vlisco has to perform as well as possible with a certain budget. Each year the maintenance department negotiates with the finance department about the size of the maintenance budget to be allocated for the following year. The maintenance department had difficulties motivating the reasons why a certain amount of money was required for the maintenance activities they wanted to perform.

Maintenance Vlisco was looking for a quantitative way to determine how to spend their maintenance budget by identifying which production facilities need most attention. The research questions were defined as follows:

1. *Taking into account budget restrictions, when to perform which preventive replacement on which production facilities to achieve the highest possible performance (in terms of money) for Vlisco?*

2. *Is the current method that is used to select the most risky facilities correct?*

3. *What are the consequences for Vlisco as a whole if the maintenance budget is increased (or decreased)?*

Model

To solve this problem a mathematical model has been developed. The model calculates the minimum total cost over the total planning horizon. The input that is used for the model consists of a list of the costs of component replacements each related to a machine. The restriction on the model is the amount of money that can be spent over the total time horizon. When the model is executed it gives the maintenance jobs that

should be performed to keep the total costs at a minimum. The costs that are minimized are the sum of repair costs and downtime costs.

Results and recommendations

The current budget situation at maintenance Vlisco leads to a total cost of €6.703.200, of which €5.292.000 are repair costs and €1.411.200 downtime costs. Based on the mathematical model this situation is almost optimal. When the maintenance budget is increased the total costs lower to a minimum of €5.869.500 (€0 downtime costs). Decreasing the maintenance budget is very risky, a 10% budget decrease already leads to 22% (€8.194.200) higher total costs.

In combination with the current methods of Maintenance Vlisco the model can be used to support the decisions about which maintenance activities to perform to keep costs at a minimum level.

It is recommended to not blindly follow the results of the model. The results of the model should be taken into consideration as an additional theoretical foundation in the decision of performing a certain maintenance job or not. The model shows that downtime costs play a big part in the decision of performing a maintenance job or not. By adjusting different input paramaters, especially the size of the maintenance budget, the influence of the size of the maintenance budget on the total costs is determined.

Results from the model are used to strengthen the position of the maintenance department to get funding for the most important maintenance activities.

Academic relevance

Lots of research has been done on the topic of maintenance engineering. The relevant studies considered in this research provided complex models each for specific situations. These often complex models were not really applicable to the situation at Maintenance Vlisco. This study provided a maintenance model specifically designed for the situation at Maintenance Vlisco. The model was also applied in a case study at Maintenance Vlisco.

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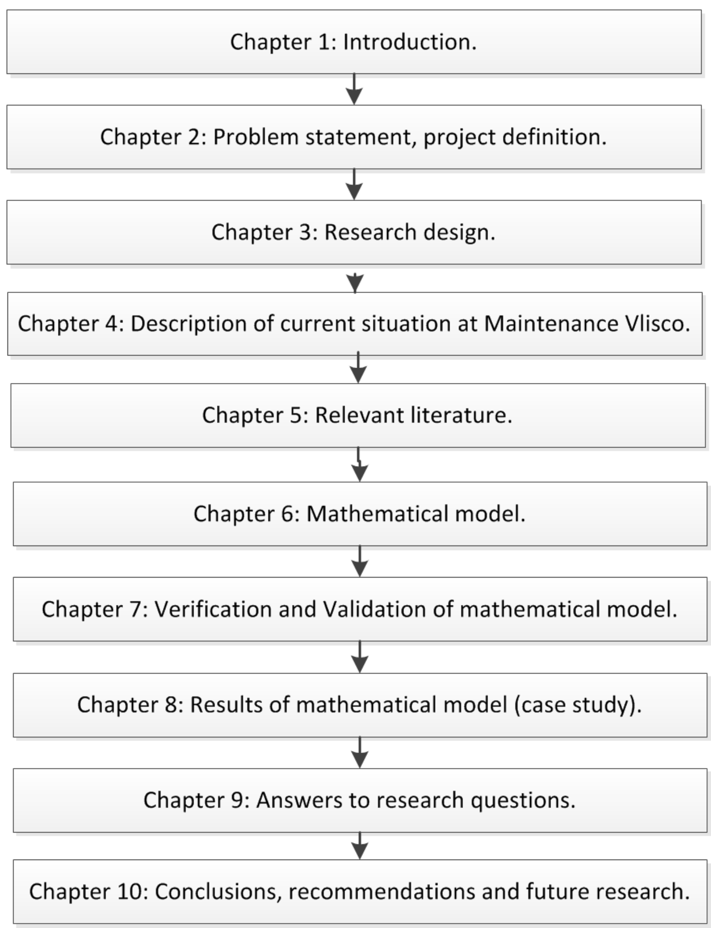
1. Introduction

This is the master thesis report for a research project that is conducted at Vlisco Netherlands B.V.. First, a company description is given followed by a description of the maintenance department where the research is conducted. Next the problem situation is described (Chapter 2) and the research assignment and research questions are formulated. In chapter 3 the research design is discussed. Chapter 4 describes Vlisco's company profile, it contains the current process that is being performed at Maintenance Vlisco. In chapter 5 the findings of the literature study are given. Chapter 6 describes the mathematical model that has been developed to answer the research questions. Chapter 7 discusses the verification and validation of the model. In chapter 8 the results with the mathematical model are described, using data provided by Vlisco. Chapter 9 answers the research questions. Finally in chapter 10 the conclusion and recommendations of this research are provided. The list of the chapters is summarized in Figure 1:

Figure 1: Outline of the master thesis report.



1.1 Deliverables

At the start of the project deliverables were specified. Below the deliverables that flow form this project are listed:

- A decision support system, implemented in software.
- User manual
- Final report and presentation

1.2 Vlisco

Vlisco is a fashion company that focuses on the African market. Since 1864 Vlisco has been designing and producing colorful fashion fabrics. The fabrics made by Vlisco play an essential role in the lively west and central African culture. Over the years Vlisco has become a very well known and popular brand. Since 2006, Vlisco strengthens her position as a brand by presenting four new collections each year. Today, Vlisco is a leader in the premium segment and her top quality fabrics are sold in more than 30 African countries. The trademark “guaranteed Dutch wax” that is printed on the edge of the fabrics is proudly worn by the people in Africa.

Vlisco Netherlands B.V., the headquarters of Vlisco, is a manufacturing company in Helmond, in the South of the Netherlands. Vlisco Netherlands is a subsidiary of the Vlisco Group. The Vlisco Group has three other subsidiaries: Uniwax, GTP and Woodin. Vlisco Netherlands produces for the top segment in the African market. The other brands, each having its own unique character, produce similar products but focus on different segments of the market. In 2010 Actis, a private equity investor which focuses on emerging markets became the owner of the Vlisco Group.

1.3 Vlisco’s production process

In this section a short overview is given of the production process of Vlisco. The production process consists of approximately 25 process steps. It can depend on the kind of product that is produced which routing is taken through the factory. A simplified overview of the production process is depicted in Figure 2.

Figure 2: A global overview of the production process of Vlisco.

At the pretreatment unit the fabric is made suitable for the chemical process it will go through. The fabric is bleached, washed, mercerized and all the threads in the fabric are “straightened”.

The next step of the production process is printing wax on the prepared fabric. When the fabric is painted, it will stay white on the places where wax has been applied.

At the fitting unit the fabric is painted with the use of a felting machine. It is called fitting because the color design is basically “fit” onto the fabric.

The fabric gets final treatments at the finishing unit. Depending on the fabric characteristic to be achieved the treatment differs.

At the final making-up unit the fabric is visually inspected for production errors. Parts of the fabric that contain severe errors are removed and considered lost product. Fabric with less serious errors is still sold but has a reduced commercial value. The final fabric is cut into standard lengths of 6 or 12 yards. Next the fabric is folded, labeled and pressed into bales. After this stage the product is ready to be sold. Most of the Vlisco’s fabrics are sold to retailers or private individuals in Africa.

1.4 Maintenance Vlisco

Vlisco Netherlands B.V. (further: Vlisco) has their own maintenance department. The goal of the maintenance department is to achieve high availability and reliability of the production facilities. According to the maintenance engineers the aim is to provide a competitive and professional service to their “customer” manufacturing.

The maintenance department consists of about 50 employees which are distributed over three types of maintenance teams:

1. Preventive maintenance

This team focusses on planned and preventive maintenance for the production facilities.

2. Service maintenance

The goal of the service maintenance team is to fix a (machine) failure as soon as possible if it breaks down. This team is 24-hour standby.

3. Support maintenance

This team focusses on planned and preventive maintenance for the utilities and support installations (e.g. pumps, piping, energy facility, resin recovery or waste-water purification).

2 Problem statement

The maintenance department of Vlisco has to perform as well as possible with a certain budget. A limited budget for maintenance activities can be a big hindrance. Too much saving on maintenance can become a problem if it leads to a machine failure with serious consequences. For instance, a major break down could result in the whole production facility being shut down. This means losing potential profits and unexpected costs on labor and materials. The other way around, spending too much on maintenance would be a waste of money.

It is difficult to answer how much money should be available for maintenance activities. When are the firm's maintenance expenditures in balance with the output that is produced? Is a higher level of availability of our production facilities worth the extra maintenance costs that are needed to achieve it? The finance department of Vlisco decides how much money will be available for maintenance activities.

Each year the maintenance department negotiates with the finance department about the size of the maintenance budget to be allocated for the following year. To get funding it is important that it can be shown that the maintenance budget is used correctly. Currently, the maintenance department has difficulties motivating the reasons why a certain amount of money is required for the maintenance activities they want to perform. It is valuable if it can be shown what the consequences of maintenance activities are for Vlisco given a certain maintenance budget.

Maintenance Vlisco is looking for a quantitative way to determine how to spend their maintenance budget by identifying which production facilities need most attention, i.e. How much money should be spent on which production machines to achieve the highest possible performance? If the consequences of maintenance activities in terms of money are known, the maintenance department will know what to decide and will have fewer problems negotiating with the finance department.

This leads to the following research assignment:

"Develop a decision support model that determines on which maintenance activities for which production facilities the maintenance budget should be spent to achieve the highest possible performance (in terms of money) for Vlisco."

The model should be able to support Maintenance Vlisco during the discussions with Finance to determine the size of the maintenance budget.

2.1 Research questions

From the research assignment the research questions can be derived. To be able to show if the maintenance budget is used correctly, Vlisco needs more insight in the effects of maintenance on the overall company performance. Currently, to decide which facilities get priority for maintenance, Vlisco is using a self-made risk matrix that identifies the most critical production facilities (see also section 4.2). For each of these facilities parts or subsystems can be preventively replaced. The maintenance department has identified many different preventive maintenance jobs that would reduce the risk that is associated with a machine. A risk is high when there is more chance a machine failure leads to a situation where it can no longer produce. Since it is not possible to replace everything due to budget restrictions a choice has to be made on which maintenance jobs to perform.

To do this, a model needs to be developed that calculates the effects (costs) over time of performing or not performing a preventive replacement. In this way it becomes clear what the best choice will be given a limited maintenance budget. When the effects of a limited maintenance budget on the total costs are known, insight can be gained into the consequences of a limited maintenance budget.

The main research question is:

1. Taking into account budget restrictions, when to perform which preventive replacement on which production facilities to achieve the highest possible performance (in terms of money) for Vlisco?

Other research questions:

2. Is the current method that is used to select the most risky facilities correct?

3. What are the consequences for Vlisco as a whole if the maintenance budget is increased (or decreased)?

2.2 Scope and boundaries

- The research will focuses on maintenance jobs that are related to a machine that is used in the production process of Vlisco.
- After discussion with the maintenance department, only maintenance activities that exceed a cost of €2.500 should be incorporated into the model.
- The maintenance budget is defined as the money that is available for performing component replacements. The costs of a component replacement consist of material- and labor costs.
- The maintenance policies used by Vlisco are assumed to be fixed and do not change during the research.
- The type of maintenance activity that is considered in this research is preventive replacements, which means that components are preventively replaced by a new component.

- If it is possible that the maintenance department uses repaired components. When these are used the components are assumed to be “as good as new”.

2.3 Chapter summary

This chapter introduced the problem situation at maintenance Vlisco: the maintenance department wants to know which maintenance activities for which production facilities they should perform to get the highest performance for Vlisco. The research questions were defined and finally the scope and boundaries of this research were given.

3. Research design

In this chapter the research design used in this research is described. The research method that is used for this research is de four phase model by Mitroff et al. (1974).

3.1 Research Method

A guideline for the development of a mathematic model is the research model developed by Mitroff et al. (1974). Mitroff et al.'s model identifies four research phases as depicted on the arrows in Figure 3:

1. Conceptualization
2. Modeling
3. Model solving
4. Implementation

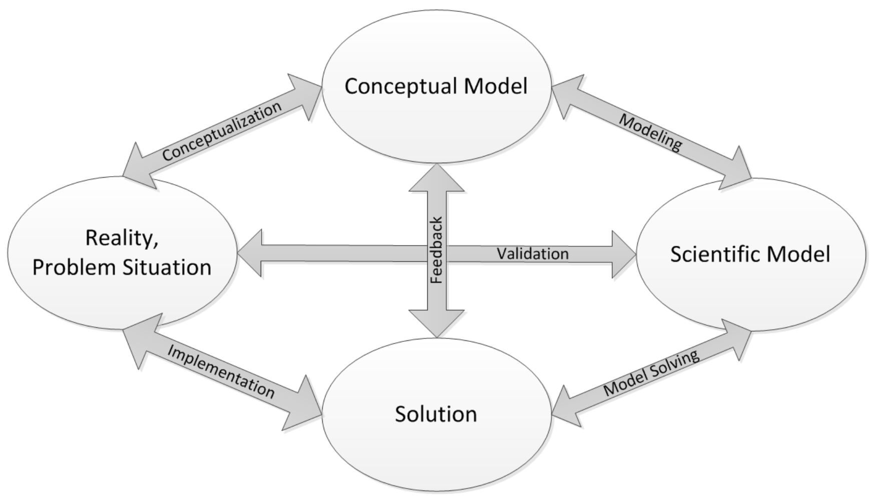


Figure 3: The research model of Mitroff et al. (1974)

Conceptualization

In the conceptualization phase, a conceptual model is developed of the problem or system that is studied. Decisions about which factors affect the problem and which variables need to be included in the model are made. All input variables and decision variables will be defined. Also the scope of the problem is addressed. It is preferable that the concepts and terms that are used are accepted or standardized in the scientific operations management literature (Bertrand and Fransoo, 2002).

Modeling

In the modeling phase the actual mathematical model is built. In this phase the causal relationships between the variables will be defined. Here a model will be developed that quantifies the relationship between the maintenance strategy of Vlisco and the overall company performance (output in terms of money).

Model solving
Once the mathematical model is developed, the model solving process can take place. Based on the model, managerial insights about how to spent the available maintenance budget for Vlisco should be gained. The model should quantify the consequences for Vlisco depending on maintenance budget that is available. By identifying the consequences in terms of money an optimal maintenance strategy for Vlisco can be derived. Also based on the findings an indication of the required budget for maintenance will be given.

Implementation
In the final phase the results of the model are implemented. Understanding the implications of a limited maintenance budget, the maintenance manager and / or his maintenance engineers will use the model to strengthen their position in the discussions with Finance about the size of the maintenance budget that is needed.

4. Current strategy of Maintenance Vlisco

Before improvements can be made it is important to identify the current situation . This section will discuss how Vlisco's maintenance department currently works and measures her performance.

4.1 Present situation at Maintenance Vlisco

There is no clear documented maintenance strategy at Vlisco. At the moment they are applying condition based maintenance (CBM). For Vlisco this means that the machine coordinator must know the state of the machine that he / she is responsible for. Problems with a machine only have to be reported if something is different from expected. Reports can be made by the machine operators. If they observe problems they inform their supervisor, which in their turn can inform the machine coordinator. The state of the machine that should be expected is not clear and mostly depends on the experience of the machine coordinator. At the moment the people on the work floor, i.e. the machine operators, the machine coordinators and the production leaders are the determining factor in the application of Vlisco's CBM strategy, because they have to monitor the state of the machines

For the maintenance activities a distinction is made between daily activities and 6-week activities. The daily activities consist of cleaning and lubricating the machines. Subsequently once every 6 weeks an estimate is made on how long it will take until a machine will fail. This estimate is mostly subjective and based on the state of the machine. Depending on the findings about the state of the machine, preventive maintenance activities are planned.

4.2 Identifying machines at risk

Maintenance Vlisco wants to spend the available maintenance budget to the greatest risks concerning the production facilities. A risk is high if a failure leads to a situation where the machines are no longer able to produce goods. Maintenance Vlisco has already been working on identifying the production facilities that are the most at risk. To identify these facilities Vlisco developed a risk matrix. The risk matrix is based on ten criteria that are rated on a level of one to four as shown in Table 1.

Table 1: Vlisco's risk matrix

Category	Criteria	Measurement	Weight factor	Level 1	Level 2	Level 3	Level 4
Probability:	Reliability	Mean time between failure (days)	1.5	> 30	5 - 30	2 - 5	< 2
	Availability	Availability (%)	1	> 97	94 - 97	90 - 94	< 90
	Chance of failure	Time to big failure (years)	3	> 5	2 - 5	1 - 2	< 1
	Alternative	Existence of alternative machines	2	Alternative machines available	...	...	No alternative machine available
	Operating risk	Maintainability of machine steering	1.2	Steering is maintainable	...	...	Steering is not maintainable
	Hardware risk	Maintainability of machine hardware	1.2	Hardware is maintainable	...	...	Hardware is not maintainable
	Knowledge risk	Available knowledge about machine	1	Knowledge is available	...	...	Knowledge is not available
Effect:	Repair time	Repair time of big failure (days)	3	<1	1 - 4	4 - 28	> 28
	Chain effect	Influence of failure on rest of machines	1.5	No influence on chain	...	...	Direct impact on chain
Trigger:	Detectability	Extent of failures detected in time	1.5	Failures recognizable	...	...	Failures not recognizable

The first column shows the three categories that are used to determine the total risk score. The category probability estimates the probability and severity of a failure for a machine. Effect measures a combination of the estimated repair time when a big failure occurs and the influence a failure has on other machines in the production chain. The definition of a big failure is not very clear and leaves room for interpretation, generally it is seen as a non-standard failure that cannot be simply repaired (up to days or weeks of repair time) Trigger measures the extent to which failures are recognizable.

In the second column the different criteria are listed. Each criteria falls into one of three categories; probability, effect or trigger. The ten criteria have been determined by the maintenance manager of Vlisco. Factors which can be controlled or are considered important from the viewpoint of the maintenance department have been included as a criterion.

The third column gives a description of how the criteria are measured, including the unit of measurement.

The fourth column gives the weight factor of the criteria.

The last four columns make a distinction between the four different levels a criterion can score. Level 1 indicates a good score on the criteria and level 4 a bad score. Both the weight factor and scores on each criterion are based on experience of the maintenance manager.

To calculate the final risk score, the probability criteria levels are all added together taking into account the weighting factors. The same is done for the effect and trigger criteria. Next the total sums of the three categories are multiplied to find the total risk score. An example of a risk score calculation is shown in Table 2.

Table 2: Example calculation of risk score.

Category	Criteria	Weight factor	Level 1	Level 2	Level 3	Level 4	Total score on criteria	Total score on category
Probability:	Reliability	1.5				X	1.5 * 4 = **6**	31.8
	Availability	1			X		1 * 3 = **3**	
	Chance of failure	3			X		3 * 3 = **9**	
	Alternative	2				X	2 * 4 = **8**	
	Operating risk	1.2		X			1.2 * 2 = **2.4**	
	Hardware risk	1.2		X			1.2 * 2 = **2.4**	
	Knowledge risk	1	X				1 * 1 = **1**	
Effect:	Repair time	3			X		3 * 3 = **9**	12
	Chain effect	1.5		X			1.5 * 2 = **3**	
Trigger:	Detectability	1.5	X				1.5 * 1 = **1.5**	1.5
Total risk score: 31.8 * 12 * 1.5 = 572.4								

By ranking all machines based on their risk score, Vlisco got a global insight in the most risky production facilities. The maintenance department reviews and updates the risk matrix every month for every machine if changes happen to the state of the production machines.

Maintenance Vlisco is still working on further developing the risk matrix. Next to the three categories a new severity category is being developed. The severity is based on four new criteria; product polarization, utilization rate, minimal buffer capacity and redundancy. Product polarization takes into account the value of the products that are produced on the machine. The utilization rate is taken into account to see if a machine is a bottleneck machine in the production process. The minimal buffer capacity quantifies the buffer that is needed between machine taking into account the mean time to repair of machines when they break down, so that when a failure occurs the output that is lost is as low as possible. The redundancy score of a machine is determined by the existence of other machines that can perform the same task.

4.3 Decision criteria for Finance

The finance department of Vlisco uses three criteria when assigning the maintenance budget. Based on an interview with the finance department the following factors came forward (in order of importance):

1. Associated machine risk (risk matrix)
2. Production volume loss during downtime (in euros)
3. Costs of investment (the cost of the maintenance activity)

The risk that is associated with a machine is the most important factor when deciding if money is provided for maintenance activities. The level of risk is determined by using the risk matrix (Table 1). The finance department distinguished four different risk profiles (Table 3) based on the distribution of the risk scores.

Table 3: Classification of the four risk profiles

Risk profile	Risk score	Percentage of total machinery
Top	> 1768	7%
High	1128 - 1768	19%
Medium	808 - 1127	17%
Low	< 808	57%

Depending on the total risk score of a machine one of the four risk profiles is obtained. How the risk score is calculated is provided in the next section, which explains how funding for maintenance activities is obtained.
The production volume (yards per hour) that is lost during machine downtime is a second factor, the bigger the production loss the more important to invest in maintenance. Currently it is assumed that every yard has the same value.
The last factor is the amount of money that is needed; the maintenance costs should be worth the benefits that are gained from performing the maintenance activity. It is the task of the maintenance department to show whether or not the cost of a maintenance activity (investment) is worth it. At the moment Maintenance Vlisco has difficulties showing whether a maintenance activity really is worth it or not. Because of this it is hard to convince the finance department that money needed for maintenance activities is justified.

4.4 Getting funding for maintenance

When the maintenance department at Vlisco identifies an issue with a machine and wants to perform a maintenance activity they have to obtain approval from the finance department if the costs of repair exceed €2.500 and the maintenance investment can be depreciated over 3 years. Recently, a form has been developed that has to be filled in to get this approval. An example of this form is provided in Appendix C. This section provides an example how funding was obtained for a recent maintenance activity on the cooling towers of Vlisco.

The cooling towers take care of the cooling-water for several machines (OHS, LDM06, DOI01) and the generating facility. The present frame of the cooling towers is heavily corroded and out of standard. The risk of corrosion is that drip catchers are no longer properly positioned and that the working of the cooling tower cannot be guaranteed.

At the start of the form, information needs to be given on which machine (and possible related machines) the maintenance activity will be executed. In this case the maintenance activity is executed on machine LWB01.

Next the risk profile as described in section 4.3 needs to be determined. This is done by using the risk matrix (Table 1) as described in section 4.2. The determination of the risk score for machine LWB01 is shown below (Table 4). When filling in the form, the risk profile of the relevant machines must be either high or top (otherwise no approval by definition). If the risk profile is either medium or low the form is not used (assuming that in that case only standard maintenance activities, such as cleaning or lubricating are needed).

Table 4: Calculation of the risk score for machine LWB01

Category	Criteria	Score	Weight factor	Weighted score	Total	Risk score
Probability:	Reliabilty	2	1.5	3	28.2	**1142**
	Availibility	1	1	1		
	Chance of failure	2	3	6		
	Alternative	4	2	8		
	Operating risk	2	1.2	2.4		
	Hardware risk	4	1.2	4.8		
	Knowledge risk	3	1	3		
Effect:	Repair time	3	3	9	13.5	
	Chain effect	3	1.5	4.5		
Trigger:	Detectability	2	1.5	3	3	

The result for the air and water treatment machine (LWB01) is a risk score of 28.2 times 13.5 times 3, which equals 1142, resulting in a “high” risk profile.

Next the total production stop (downtime) is calculated based on an estimate of the delivery time for the components that are needed for repair and the time of repair for the machine itself (on the form: MTTR). Other activities that take time (such as setup time) before a machine can produce again is filled in the field *other* below MMTR. For this calculation it is assumed that there are no spare parts on hand. The total production stop time is later used to calculate the loss of production. This results in a total production stop time (hours). Based on information from the suppliers of the components that are needed for repairing machine LWB01 it is estimated that the delivery time is 9 days (9d * 24h = 216 hrs). The estimated time for the maintenance activity itself is 5 hours, resulting in a total production stop of 221 hours for machine LWB01. The finance and maintenance department assume that this will be the total time machine LWB01 will be down due to failure if no preventive repairs will be performed (before the machine fails).

In the next step the normative loss of production (amount of lost sales in k yards) is calculated by multiplying the production speed in yards per hour of the considered machine by the total production stop time (each machine has only one production rate). This amount is normalized by the impact the machine has on the total production flow of Vlisco. To do this, the normative loss of production is multiplied by the utilization rate of the machine (%). The machine speed in yards per hour and the utilization rate of the machine are taken from the yearly capacity calculations. All of these estimates come from the planning department of Vlisco. For machine LWB01 the estimated loss of production equals: $221\ hours *$ [redacted] $=$ [redacted] $k\ yards$.

Based on historic information and experience the sales department assumes that a total of 10% of the maximum factory output can be compensated. For example when a customer made an order of 100 k yards and only 90 k yards were delivered by Vlisco the customer will order 10k yards more the next time. When the form of LWB01 was filled in, the maximum factory output was set at [redacted] k yards per week. This means that in this case the compensatable loss of production by sales is [redacted] k yards. The result for machine LWB01 is an estimated total loss of sales of [redacted] k yards.

In the final step the total investment costs are compared with the risk limitation (expressed in terms of euros) of the maintenance activity. The margin of Vlisco's product is set at [redacted] euro per yard (based on the difference between sale price and cost of production). This results in a risk of lost cash of [redacted] $euro\ per\ yard *$ [redacted] $k\ yards =$ [redacted] $k\ euro$ if machine LWB01 will break down due to not performing the needed preventive maintenance activity.

The total cost of the maintenance activity (replacement investment) for the cooling-tower is 3.5 k euro. For the LWB01 machine this results in a positive risk limitation of [redacted] k euro.

The form (Excel sheet) is only used as a tool by the maintenance engineers. It does not mean if the risk limitation is a positive number that the maintenance activity will always take place. Maintenance engineers will still have a meeting with the people of Finance responsible for the maintenance budget. In these weekly meetings the activities that maintenance wants to perform are discussed with the people from finance and a final decision is made. The project of replacing the frames of the cooling towers was approved due to the high positive risk limitation and the convincing voice of the maintenance engineers that this activity was really needed.

The current weekly meetings between Maintenance and Finance is only a temporary situation. There is still a learning process and for every maintenance activity that is needed maintenance has to fill in a form in to get approval from finance. The goal of maintenance is to go to a situation where it has identified every needed (or possible) maintenance activity that has a high or top risk profile. When all needed maintenance activities have been identified the goal is to perform the most important maintenance activities without exceeding the maintenance budget for repairs.

The management of Vlisco sets a yearly maximum amount of money that can be spent on maintenance activities. Currently, the yearly budget that is available is approximately [redacted] k euro per year. This budget includes all operating expenditures (OPEX) as well as the capital expenditures (CAPEX). The OPEX are about [redacted] k euro per year and the CAPEX are about 2.000 k euro per year. This budget is based on the spending of previous years, and equates to about [redacted] euro per yard. The yearly budget plans that are made must also be approved by the finance department. When the yearly budget is known, the maintenance department has to make a maintenance budget plan that describes the available budget per month. This budget is almost the same for every month, except during the month July where the 2-week summer stop is planned. During this period a lot more maintenance activities are performed. It is possible that the real expenditures for a month were lower than the costs budgeted. When this happens the money will still be available for maintenance activities later in time. It is in almost no case allowed to go over the maintenance budget. When this happens, the finance department will not approve any more spending.

4.5 Measuring the performance

To measure her performance the maintenance department of Vlisco keeps track of different indicators. Vlisco Maintenance distinguishes four key performance indicators (KPI), see Table 5:

Table 5: KPI's of Maintenance Vlisco

Key performance indicators (periods of one week)	Target
Total number of failures	No specific target
A failure lasting longer than 2 hours (bottleneck machines only)	Max. 5 failures
A failure lasting between 1 and 2 hours	Max. 10 failures
A failure that lasts for longer than 2 hours	No specific target

For the measurement of the KPI's a failure is only taken into account as a failure when machine downtime was reported. Machine downtime is defined as the time a machine cannot fulfill its intended function during it's scheduled production time (see also Figure 4 in section 4.6).

The KPI's use weekly targets. The scores on the four KPI's are summarized per machine in the weekly KPI overview of maintenance (only for the bottleneck machines). The bottleneck machines are determined weekly by the planning department and depend on the predicted utilization that is calculated based on the production planning.

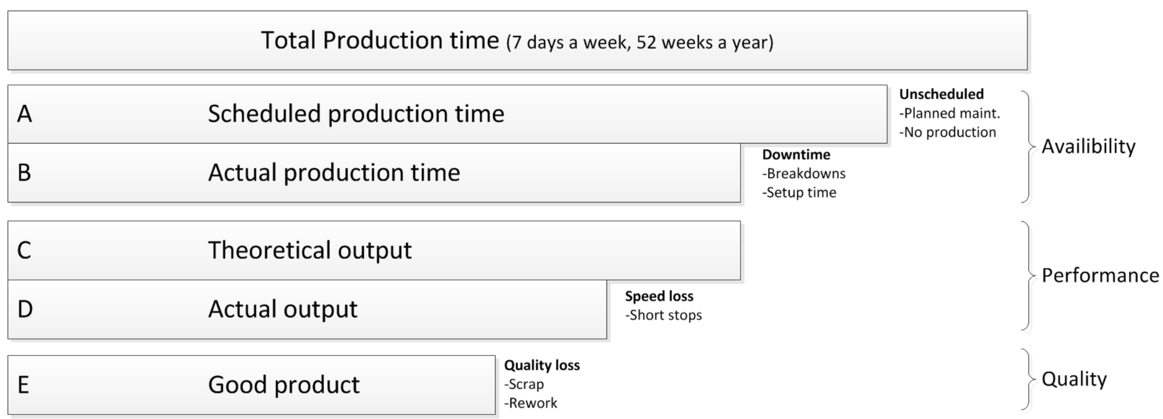
Maintenance Vlisco also keeps track of the reliability and average repair time of the production facilities. To measure the reliability Vlisco calculates the mean time between failure (MTBF). For Vlisco MTBF is defined as the total scheduled production time for a machine divided by the number of times a machine failure occurred during this scheduled production time. The average repair time is calculated by the mean time to repair (MTTR). Vlisco defines MTTR as the total repair time divided by the number of failures. These times are determined by using the software program Maintenance Control described in the next section. The total repair time is based on the difference between the time a machine failure is reported and the time the machine is producing again.

4.6 Data

Vlisco collects and stores data about her production facilities by using customer made software. The two software programs that are used to support and keep track of the production facilities are the Overall Equipment Effectiveness (OEE) toolkit and Maintenance Control.

OEE toolkit

With the OEE toolkit the effectiveness of the machinery is tracked. From Vlisco's point of view the difference between the theoretically possible- and actual production is a loss. To get insight into the production losses the OEE toolkit was developed. Figure 4 summarizes the OEE formula that is used by Vlisco.



OEE = (B / A) * (D / C) * (E / D)

Figure 4: Determination of OEE value by Vlisco (documentation OEE toolkit, 2013).

Each day during production, machine operators enter data about the status of the machine. The most commonly used states of the machines are: production (including production speed), setup time, (planned) maintenance and breakdown. Based on this data, the OEE toolkit generates an OEE value. The data that is stored in the OEE toolkit is shown in Table 6. The first column states the part of the OEE formula that is considered, the second column gives the name of the field used in the OEE toolkit and the last column gives a description of the data field.

Table 6: Description of the data stored in OEE toolkit.

OEE factor	Data	Description
Availability	Total time recorded	The scheduled production time (minutes).
	Total production time	Total time machine was producing (minutes).
	Total downtime	Total time machine is standing still and is not producing (minutes).
Performance	Output goal	The theoretical output that is set (yards).

	Speed loss	The speed loss, this value is always set to 0 (%).
	Short stops	Output loss due setup time of machine (yards).
Quality	Actual output	Actual produced output (yards).
	Good product	The amount of good product of the actual output that is produced (yards). The amount of good product is always set to 100% of the actual output in the OEE toolkit.

Software program Maintenance Control

The software program Maintenance Control gives an overview of maintenance activities within Vlisco. Via the software program any department can request repairs (maintenance) when needed. If a failure is reported, a notification message will pop up in Maintenance Control which enables the service maintenance team to respond quickly. First, an assessment is made by the machine coordinator about the urgency of the failure that is reported. If immediate response is needed, the service maintenance team will handle the failure as soon as possible. If the reported failure is not that urgent (i.e. there is no machine downtime involved) the needed maintenance activities will be scheduled at a later point in time. When possible, the activities will be included in (preventive) maintenance activities that were already planned before.

A notification can have three different states: open, in process and ready. If the process is followed correctly, data is stored about the following (Table 7):

Table 7: Description of the data stored in Maintenance Control.

Data	Description
Status	The status of a notification can be open, in process or ready.
Notification location	The production unit that made the notification to request maintenance.
ID	ID number of the notification.
Notification name	The title of the notification.
Notified by	The name of the employee that made the request for repairs.
Notified date	Date and time of the notification.
Active by	Name of person that handles the request for repair and initiates the needed maintenance activities
Active date	Time when maintenance process started.
Finished by	Name of person who closed the notification (ready).
Finished date	Time when notification is closed.
Response time	Amount of time taken to respond to the notification.
Downtime	Amount of downtime for machine (if any).
Priority	Priority level of the notification.
Cause	Cause for the maintenance requirements.
Description	Description of the problem observed.

A history of all notifications is stored in the database of Maintenance Control since the year 2002.

4.7 Chapter summary

The present situation at Maintenance Vlisco was discussed. Next the method of identifying the machines at risk by using the risk matrix was described. Also the process of obtaining funding for maintenance was described. The form described how funding for maintenance activities is obtained for the current situation at Vlisco. The calculation for the risk of lost cash is comparable to the concept of downtime costs if a machine is unable to produce due to a failure. Finally the method used by Maintenance Vlisco to measure her performance was discussed.

5.1 Relevant literature

To acquire the most knowledge and insights about the research problem a extensive literature study has been performed. In this chapter the relevant literature with respect to the research problem is discussed.

5.1.1 Keywords

The keywords and databases that have been used to conduct the literature search are displayed in table 6. Combinations of search terms have also been used. A star behind a key word replaces zero or more characters at the end of a term. i.e. Recruit* can return recruits, recruitment, recruiting, etc.

Table 8: Keywords used in the literature search

Databases considered	Keywords used
ABI/Inform	Maintenance AND Budget
JSTOR: the Scholarly Journal Archive	Maintenance AND Priorit*
Web of Science	Maintenance AND Model*
Google Scholar	Maintenance AND Risk Risk AND Priority AND Maintenance Risk AND Assessment AND Maintenance Criticality AND Maintenance Facilities AND Condition AND Assessment

5.1.2 The basics of maintenance

The classic view of the role of maintenance is to fix broken items. With this narrow perspective maintenance remains to the tasks of only repairing or replacing items that have failed (Jardine & Tsang, 2006). Today, this strategy is best known as corrective maintenance. A broader view for the definition of maintenance is given by Geraerds (1985):

"Maintenance is all activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfillment of its production function."

Furthermore Geraerds (1985) distinguishes between the main two categories of performing maintenance: *Corrective Maintenance* (CM) and *Preventive Maintenance* (PM). Corrective maintenance takes place after a failure event; the objective is to restore the entity which fulfills a relevant function in the production process to the physical state that is needed to fulfill its production function again. Preventive maintenance takes place before a failure event; the objective is to reduce the probability of failure in the future of the production unit.

To most widely used concepts to monitor the performance of maintenance activities are reliability, availability and maintainability (Murty & Naikan, 1995).

Reliability is defined as the probability that a system will perform its required function for a specified period of time under a given set of operating conditions (Lewis, 1995). The most-used parameter to describe the reliability of a system is the *mean time to failure* (MTTF) or *mean time between failures* (MTBF) when a system is repairable. MTTF is the expected time to failure of a system, whereas MTBF is the expected time between two subsequent failures of a system. *Mean time to repair* (MTTR) is often used to measure the maintainability of repairable items. It is defined as the average time needed to repair a failed component or system. *Availability* is the most important expression for the evaluation of repairable systems (Murty & Naikan, 1995). It is defined as the percentage of time the production facility is performing its intended function. When measured over a long period of time, the following formula can be used to determine availability:

$$Availabilty\ (\%) = \frac{Total\ uptime}{Total\ uptime + Total\ downtime} = \frac{MTBF}{MTBF + MTTR}$$

However, the use of this formula has several drawbacks. When using this formula it is assumed that:

- the failure is immediately noticed,
- repairs are started immediately,
- machines are immediately producing again after repair.

In reality this is often not the case. So from a practical point of view it is better to measure availability by the following formula:

$$Availabilty\ (\%) = \frac{MTBF}{MTBF + MDT}$$

Where MDT is the *mean down time* of the system defined as the average time that the system is not able to perform its intended function. As mentioned before, availability is a very important factor in evaluating the reliability of a system. However, this does not imply that the availability of a system should be as high as possible. When system availability is plotted against profits (net income), it will result in a graph similar to the graph in Figure 5.

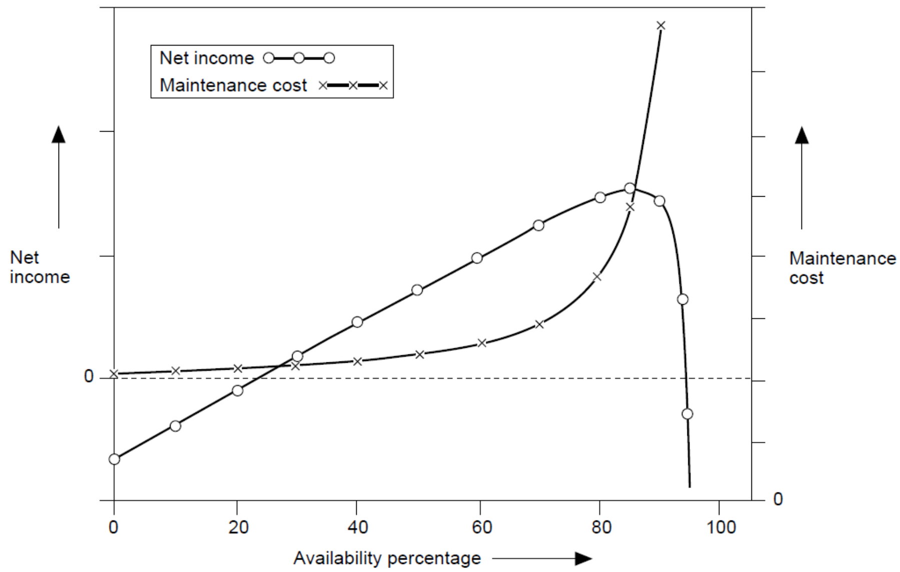


Figure 5: Cost of maintenance versus net income against plant availability (adapted from (Murty & Naikan, 1995)).

For very low values of availability maintenance costs are extremely low but the firm is running a negative net income. Increasing the money spent on maintenance the availability percentage will increase and a point is reached where the maintenance cost equals the net income. Going further on the line, net profit will increase with higher levels of availability until a maximum point is reached. When further increasing the availability percentage net profit will decrease again until net income equals the maintenance costs again. From this point on, increasing availability will result in a net loss. According to Murty and Naikan (1995) the amount that is available for maintenance is the most important factor in estimating the required availability of a firms machinery. This graph is important to realize that it does not have to be optimal to have an as high as possible availability percentage for each production machine. For example, to get the availability level of a production machine from 97% to 98% might not be worth the costs.

5.1.3 The cost of maintenance

The focus of this research is on the effect of a limited budget for maintenance activities on the overall company performance. In the literature many studies have been done on maintenance problems. In many of these studies the key business objective of maximizing profits is often neglected and frequently maintenance is purely seen as a cost. Costs can easily be translated into economic value. If savings are made on the maintenance budget it has an immediate (positive) impact on the operating profit. At least this is often assumed, not knowing what the consequences on the production facilities can be. Savings in the maintenance budget can have detrimental effects on the availability or safety of the production facility in the short- or long-term. It can lead to wrong decisions if the relationship between maintenance activities and the company performance is not fully known (Haarman & Delahay, 2004). So it can be valuable to identify what the effect of a certain maintenance strategy is on the company performance.

The dominant consequence of machine failure is widely regarded as the cost of loss of production (Geraerds, 1985). In practice it appears to be very hard to determine the exact costs of lost production that are needed in the trade-off against the cost of maintenance activities. The question if company output (profits) is in balance with the manpower and materials used are the main challenge faced by maintenance engineers (Dekker, 1996). Geraerds (1985) states the challenge originates from the inadequacy of the models that are used in determining the cost of loss of production. Another issue is that lowering the costs of lost production is considered as an indirect cost (Dekker, 1996). Savings in these costs are less tangible and thus less convincing to upper management. Another reason why it is hard to determine the costs of downtime is that it depends on several other system parameters like production rates and the existence of redundant equipment or alternative production methods. Having a good estimate of downtime costs has several benefits (Pascual, Meruane, & Rey, 2008):

1. The impact of equipment on the total system efficiency can be measured
2. It can be used to assess the performance of different maintenance policies
3. It can be used in decision making problems, such as maintenance strategies.

Also important factors as time and budget constraints are often overlooked, while these factors have the biggest influence on the decision making of (maintenance) managers (Tam & Price, 2008). Tam and Price (2008) developed a maintenance prioritization model that incorporated these two factors. Tam and Price see maintenance as any other business function and that's why maintenance activities also have to be prioritized on return on investment. To accomplish this they introduced three indices: a maintenance investment-, time- and budget index. The maintenance investment index is a ratio between risk reduction and the cost of the maintenance activity. To determine the value of this index the time- and budget index are used. The time index indicates how much time it costs to perform a maintenance task. The budget index is the ratio between the money that is needed for a maintenance task and the total budget that is available for maintenance (within a given period of time). When all possible maintenance activities have been evaluated they are ranked and added to a maintenance plan based on priority. Depending on time or budget constraints only the tasks with the highest priorities are executed.

5.1.4 Selective maintenance

At Vlisco the limited amount of money that is available is the main resource that limits the amount of maintenance actions that are performed. Performing maintenance under limited resources is known in the literature as selective maintenance. In the literature many models have been developed to assist with making selective maintenance decisions (Cassady, Murdock Jr, & Pohl, 2001) (Liu & Huang, 2010) (Maillart, Cassady, Rainwater, & Schneider, 2009). According to Cassady et al. (2001) identifying the critical maintenance activities is part of selective maintenance. To optimize a systems performance (i.e. reliability) this involves making decisions on whether to maintain (continue to use without repairing) or repair system components. These relevant articles with respect to the problems and activities of maintenance Vlisco have been explored. In Table 9 a summary is given that contains the important elements for this research problem compared to the articles in literature.

Table 9: Summary of maintenance models

	Multiple machines	**Multiple components**	**Limited budget**	**Downtime costs**	**Machine / Component life**	**Case study**
Murty & Naikain, 1995	No	No	No	Yes	-	No
Pascual, et al., 2008	No	No	Yes	Yes	Deterministic	No
Tam & Price, 2008	No	Yes	Yes	Yes	Stochastic (Weibull)	No
Cassady, et al., 2001	No	Yes	No	No	Stochastic (Weibull)	No
Maillairt,. Et al., 2009	Yes	Yes	No	No	Deterministic	No
Liu & Huang, 2010	Yes	Yes	No	Yes	Stochastic (Weibull)	Yes
Maintenace Vlisco	Yes	Yes	Yes	Yes	Deterministic	Yes

The studies in the table provide complex models each for a specific situation. These often complex models are not really applicable to the situation at Maintenance Vlisco. This study provides a maintenance model specifically designed for the situation at Maintenance Vlisco. The model is also applied in a case study at Maintenance Vlisco.

5.1.5 Risk assessment

The risk matrix of Vlisco determines the most critical facilities for Vlisco. Prioritization of preventive maintenance tasks is based on the ranking on these risk scores. Since the risk matrix plays an essential role in the maintenance strategy of Vlisco, also literature covering risk assessment is reviewed.

The strategy of the maintenance department corresponds most to the framework of risk based maintenance, which consists of two phases: risk assessment and maintenance planning based on risk. When carrying out risk based maintenance, the risk assessment is the most important phase since the maintenance decision are based on the assessed risk as centre (Arunraj & Maiti, 2007). According to Nieuwhof (1985) risk can be defined as “the considered expected loss or damage associated with the occurrence of a possible undesired event”. To identify the most high risk operations, different techniques are used, but in the end it always boils down to identifying the potential threats, estimating their probability and finally estimating the consequences. The general process of risk assessment is shown in Figure 6.

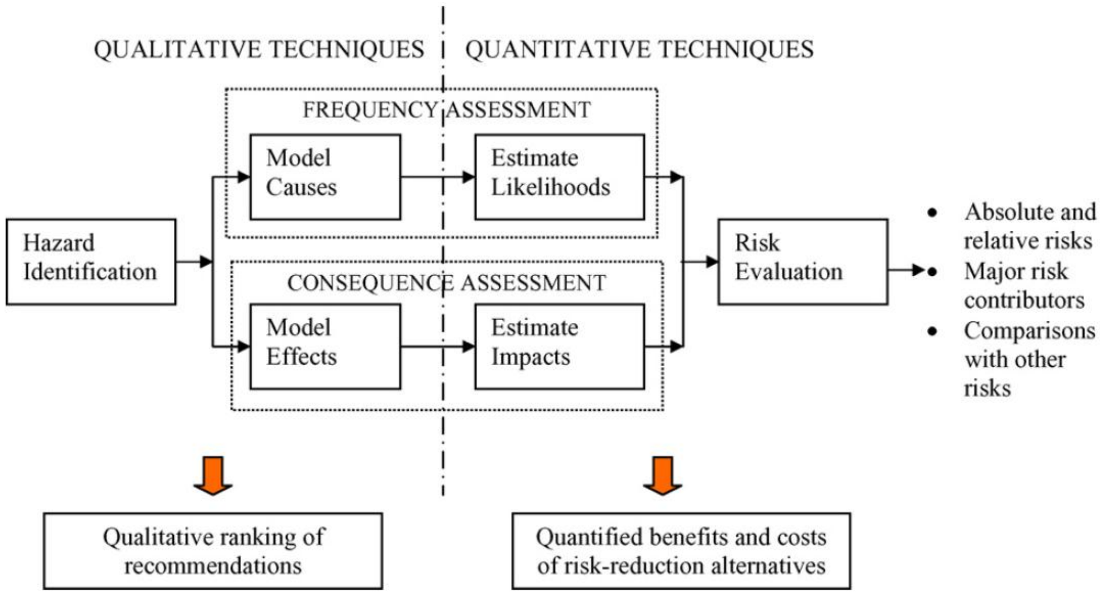


Figure 6: The risk assessment process (adapted from Arunraj & Maiti (2007))

The process starts with the identification of the possible hazards, which are the sources of loss or damage. Next the number of times these hazards occur per time interval need to be estimated, this is the frequency assessment. Consequently the impact of the possible hazards need to be identified, this is the consequence assessment. Combining the two assessments a total risk evaluation is made.

As mentioned in section 4.2 the risk matrix of Vlisco identifies the production machines that are the most at risk based on three categories: probability, effect and trigger. This method is comparable with parts of the concept of failure mode and effect analysis (FMEA) in literature. FMEA is a technology that is used to collect data on possible failure modes and the criticality of these failures modes:

"FMEA is a design and analysis technology that is directly applicable to failure and prevention. The technology provides a structured systematic identification of the potential failure modes in design or manufacturing, then by studying the impact of failure to the system, provides a qualitative evaluation of the necessary corrective actions by focusing on the problems affecting systematic reliability (Chen, 2007)*."*

A FMEA also starts with the identification of possible failure modes. Next an assessment on a scale of 1 to 10 is made of the likelihood the failure modes occur, the severity (consequences) of these failures and an assessment if the failures can be detected on time. Based on these three assessments a measure of risk is calculated for each failure mode (Gilchrist, 1993). To determine this risk level in FMEA, the risk priority number (RPN) is used. The RPN is calculated by multiplying the scores on the three risk factors: severity * occurrence * detection. In a FMEA improvements are addressed to machines in an order of higher to lower risk.

The RPN calculation is used to value potential problems; if every problem is valued they can be ranked in order. If the RPN falls within a pre-determined range, preventive maintenance actions may be recommended to reduce the risk (Raheja & Gullo, 2012). Typically preventive actions are first performed on the facilities having the highest RPN. Also the larger the RPN the more opportunity for improvement. The principle of FMEA is very similar to the process followed at the maintenance department of Vlisco. Section 4.3 described the classification of risk profiles, which are used in the decision if preventive maintenance actions will be performed at all as described in section 4.4.

5.2 Comparison of Vlisco's risk matrix with literature

The risk matrix of Vlisco plays a very important role in the maintenance strategy of Vlisco. This section validates and compares the concept of Vlisco with the concepts mentioned in literature.

Parts of Vlisco's risk matrix cover the concepts discussed in literature. For each machine at Vlisco an estimation of the reliability of the machine is made. Also the effect of a big failure (worst possible case scenario) is measured based on an estimation of the repair time of the failure and the effect the machine failure has on the other machines in the production chain.

Comparing the RPN concept to the categories of Vlisco's risk matrix, it can be concluded that probability corresponds to occurrence, effect to severity and trigger to detection. Since the risk matrix ranks machines instead of possible failure modes there is basically only one failure mode considered per machine. This is also reflected in the thought of the scoring on the ten criteria, where a machine is "only as strong as its weakest link" or that only the chance of failure for the worst possible scenario is considered.

Further comparing Vlisco's risk matrix with literature the following points came forward (Table 10):

Table 10: Comparison with risk matrix of Vlisco with literature.

Different, but no significant impact.
RPN rating scales range from 1 to 10, while the risk matrix only ranges from 1 to 4.
Different, but improved compared to standard literature.
RPN gives equal weight factors to severity, occurrence and detection. In most articles this is seen as a drawback of the RPN concept. Firms may decide that severity is a more important criteria than occurrence or detection. Vlisco incorporated this by giving different weights to the different criteria.
In accordance with literature, but hard to improve.
Risk priority numbers heavily rely on the judgment of (maintenance) experts. Same for the risk matrix of Vlisco. There are no clear guidelines for rating the different scales, which makes risk scores always subjective.
Partly in accordance with literature, but room for improvement.

Both RPN and the risk matrix of Vlisco consider three factors: probability of failure, severity and the detection of failures in a timely manner. The economical aspect is neglected in the calculation of the value for effect in the matrix of Vlisco. This can be incorporated in the effect calculation of a possible failure mode.
The risk matrix is on machine level, there is no distinction in sub components of the machines. The risk matrix does not identify different failure scenarios per machine. In determining the scores of the criteria *chance of failure* and *repair time* the worst case scenarios are considered.
The biggest weight factor is given to the category probability. Since the probability category is based on seven criteria it gets a very high average score even if the individual scores on the criteria are low. This can be avoided by lowering the weight factors for the seven probability criteria.
The maintenance activities are based on the associated risk of the machines. Another important aspect is the (planned) utilization rate of the machine. Some machines might temporarily have a higher utilization rate based on the production planning of the upcoming period. During this period it is important that the machine is available as much as possible: the relative importance of a machine to the overall production capacity of the firm can change over time as the product mix changes, which creates different bottleneck / critical machines over time (Gopalakrishnan, Ahire, & Miller, 1997).This means that Vlisco should always keep updating the risk matrix with the latest information available.

5.2.1 Chapter summary

Literature related to research problem was discussed. First the most widely used concepts in the maintenance literature were defined. Different selective maintenance models were studied and compared to see if they could aid in the development for the model that needs to be developed for Maintenance Vlisco. Also literature related to risk assessment was discussed. The risk assessment process by Arunraj & Maiti (2007) described a technique to identify the biggest risks. The idea of quantifying costs and estimating likelihoods will be used in the development for the mathematical model of Vlisco. Finally a comparison with literature and the risk matrix of Vlisco was made.

6. Mathematical model

This chapter describes the mathematical model that is used to answer the research questions and solve the problem discussed.

6.1 Sets, parameters and variables.

This section defines the sets, parameters and variables that are used in the model. Table 11 gives an overview of the sets and parameters that are used.

Table 11: Sets, parameters and variables

Sets	**Definition**	**Unit**
C_m	The total number of components for machine m that are considered in the model and have a time to failure smaller or equal than the total time horizon T.	Integer
m	Machine number, m ∈ {1, 2, …, M}.	Integer
M	The total number of machines considered in the model (all machines that have at least one or more replacement).	Integer
T	Total time horizon in periods.	Integer
Parameters	**Definition**	**Unit**
B	Total budget available for replacements during T.	Euro
C_{mc_m}	Costs of repair (materials + wages) for component c_m related to machine m.	Euro
L_{mc_m}	Remaining life time of component c_m related to machine m counting from the start of the planning horizon (in periods).	Integer
Cd_m	Costs of downtime per period for machine m.	Euro
Decision variables	**Definition**	**Unit**
X_{mc_m}	Variable representing if the replacement for component c_m related to machine m is performed: a value of 0 indicates no, a value of 1 indicates yes.	Binary

6.2 Model description

The model calculates the minimum total cost over the total planning horizon T. The model only considers machines that have known maintenance jobs during T; these are the so called replacement investments. For each component the remaining life time (starting from the beginning of the planning horizon) is given if the replacement investment would not be carried out, represented by the variable L_{mcm}. Figure 7 depicts the status of a machine with one replacement, where L_{mcm} equals 3 periods. The blue line represents the first 3 periods that the machine works as intended, but without the interference of maintenance the machine will break down after these 3 months, after which it can not be used.

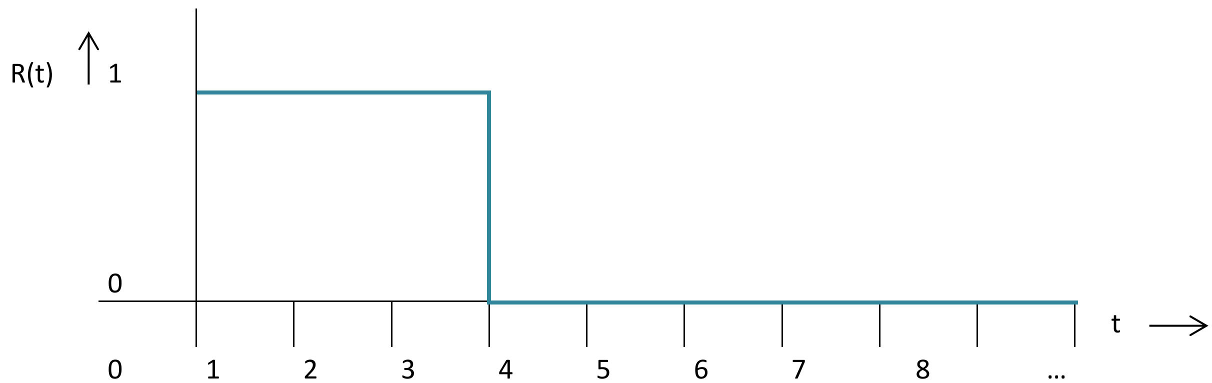


Figure 7: Reliability of a machine if L_{mcm} = 3.

The model uses a rolling horizon. This means that the model can be periodically solved and evaluated based on the most recent information that is available. If changes happen and the expected wear of some components are estimated to be higher or lower the value of L_{mcm} can be modified accordingly. Also if a component (machine) breaks down earlier than expected, the value of L_{mcm} can be adjusted to the period it broke down.

If the prices of material or labor change, the parameter C_{mcm} can be adjusted accordingly to a new cost of repair. Another important parameter, Cd_m, the costs that are associated with downtime for a machine can be adjusted. In the case where everything that is produced can be sold, the costs of downtime are higher than in a situation where this does not apply. Also the importance or the impact a machine has on the rest of the production chain can increase the value of Cd_m.

Determining the input parameters

Currently, the input parameters are mostly based on experience. The number of machines (M) and components (C_m) result directly from the maintenance investments that are identified by the maintenance department. These maintenance investments are all activities that need to be performed in the future, if not performed the machine will break down. In this research the horizon is fixed at 36 months (T), but can be changed if needed. The budget (B) is set at the amount of money that is available to perform preventive maintenance activities. It consists of the money available for materials and the money available for labor. For each maintenance investment the total costs of the repair are determined (C_{mcm}) by again adding up the cost of material and the estimated labor costs to perform the replacement. The remaining life time (L_{mcm}) of a component is presumably the hardest parameter to determine for Vlisco. Currently, the remaining lifetime is estimated by the maintenance engineers or the maintenance manager itself. The premise was that this parameter would be estimated from the data that is provided in the software program maintenance control, as discussed in section 4.3. But it appeared that this data was most uncertain due to many incomplete fields or extreme numbers (that were certainly incorrect) and could not be used in the research. The downtime costs per machine (Cd_m) are the total costs for a machine if it is not producing for one period. Currently, the downtime costs are split into four different levels (€33.600, €84.000, €168.000, €1.008.000) based on the category effect in the risk matrix of Vlisco. Ideally, these costs are determined in a more precise manner. For each machine different factors can be taken into account. The production speed, type of product (higher or lower profit margin), utilization rate can all affect the costs of downtime of a machine.

Model Assumptions

The assumptions which are made in the mathematical model are follows:

1. Repair time is assumed to be zero (no capacity restrictions). The purpose of this research is to analyze the effects of a restricted maintenance budget on the company performance. With the time periods that are used the repair time is considered to be negligible.

2. The possible maintenance jobs (replacement investments) are all known beforehand and are gathered during the routine inspections by the maintenance department. Each replacement investment has an associated estimate of how long the machine will continue to work if the maintenance job is not performed.

3. Each maintenance job that is specified is carried out only once. So a maintenance job is either performed, or not. The maintenance jobs that are considered in the model are all expected to have a long life span. That is why it is assumed that the machine components keep working till the end of the total time horizon.

4. A machine has only two possible states. A machine works as intended or it has failed. Vlisco production facilities are quite orthodox, they either run at full speed or not at all.

5. Every possible maintenance job that is considered in the model has a value of L_{mcm} that is lower or equal to the total planning horizon T. If the lifetime of a component is longer than the total planning horizon, the component will not fail at all during the planning horizon. Hence, it would not be needed to include the component in the list of maintenance jobs.

6. Downtime costs per period are equal for all periods.

7. The budget that is available for replacement investments can be freely divided over all periods.

8. A machine fails if one or more component has failed. From a reliability point of view this is comparable to a system in series. The concept of a series system is that if any of the system components fails, the entire system fails.

6.3 Model formulation

To minimize the total relevant costs of every machine in the model over the total planning horizon T, a mixed integer programming approach is used. The objective function minimizes the total relevant costs over the total planning horizon T:

$$Minimize\ TC\left[X_{1c_1}, \dots, X_{mc_m}\right] =$$

$$\sum_{m=1}^{M}\left(\sum_{c_m=1}^{C_m}[(T-L_{mc_m})-(T-L_{mc_{m+1}})](1-X_{mc_m})\right)*CD_m+\sum_{m=1}^{m}\left(\sum_{c_m=1}^{c_m}X_{mc_m}*C_{m_{cm}}\right) \quad (1)$$

s.t.

$$\sum_{m=1}^{M}\sum_{c_m=1}^{c_m}X_{mc_m}*C_{mc_m}\leq B \quad (2)$$

$$\forall(m,c_m), m\in\{1,\dots,M\}, c_m\in\{1,\dots,C_m\}: X_{mc_m}\in\{0,1\} \quad (3)$$

$$\forall(m,c_m), m\in\{1,\dots,M\}, c_m\in\{1,\dots,C_m\}: X_{mc_m+1}\leq\ X_{mc_m} \quad (4)$$

$$\forall m, m\in\{1,\dots,M\}: L_{mC_m+1}=T \quad (5)$$

(1) The objective function minimizes the sum of the total downtime and repair costs The first part of the sum indicates the total downtime costs due to repairs that are no performed. The second part of the formula calculates the total costs of repairs. An explanation of how the part of the formula that calculates the downtime works can be found in appendix G.

(2) The sum of the material costs per period cannot exceed the maintenance budget that is available for repairs.

(3) A maintenance job is either performed or not performed. X_{mcm} has a value of 1 if the maintenance job is performed and zero otherwise.

(4) Component repairs per machine are performed in order of remaining life time, from lowest to highest. The component that fails first also needs to be repaired first. If this component is not repaired it has no value to replace other components for the same machine that fail at a later point in time.

(5) This restricting is needed to calculate the total downtime for a machine. A dummy variable is needed that has a value equal to the total time horizon. This is used to calculate the downtime until the end of the horizon (if any).

6.4 Risk matrix compared to mathematical model

The developed mathematical model provides an objective way in the decision of performing or not performing a certain maintenance job. A comparison with the elements in the risk matrix of Vlisco and the elements in mathematical model is made in Table 12.

Table 12: Risk matrix of Vlisco compared to mathematical model

Category	Criteria	Mathematical Model
Probability	Reliability	The reliability is translated by the parameter L_{mcm} in the model. It represents the remaining life time of a component. If the remaining life is short, reliability can be considered low, if the remaining life time is longer reliability can be considered higher. How the reliability is modeled is also shown in Figure 7. Reliability is defined as the probability that a machine will perform its required function for a specified period of time (Lewis, 1995). In this model the probability that a machine component keeps working is 100% until the time to failure of that component is reached (after the time to failure, it is 0%).
	Availability	Machines stop working if maintenance jobs cannot be performed after the component life has been reached. When components are repaired in time machines keep working. This can be seen as a machine being available or unavailable.
	Chance of failure	The chance of failure is also translated by the parameter L_{mcm} in the model. Essentially the chance of failure is 100% in the model, the machine component fails at the exact period in time that is given by the remaining component life L_{mcm}.
	Alternative machines	The existence of alternative machines is translated into the parameter $Cd_{m.}$ If machines exist that can perform the same job as another machine the costs of downtime for a machine are likely to be lower.
	Operating risk	The risk in the maintainability of the steering of a machine can also be translated into the parameter Cd_m. If operating risks are higher the downtime costs for a machine are likely to be higher if something goes wrong.
	Hardware risk	The risk in the maintainability of hardware of a machine can be translated into the parameter Cd_m the same way as operating risk is translated. If hardware risks are higher the downtime costs for a machine are again likely to be higher if something goes wrong.
Effect	Repair time	Repair time is assumed to be zero in the model. So repair time is not directly translated into the model.

	Chain effect	If a machine failure has a big influence on the rest of the machines in the production chain the costs of failure for that machine will be very high. This can be translated into the parameter machine downtime cost per period Cd_m.
Trigger	Detectability	If failures are recognizable in time it is likely that the impact of machine failure is lower (because you see the machine failure coming). Again, this can be translated into the machine downtime parameter Cd_m. If a failure is recognizable the value of Cd_m can be adjusted to a lower value, vice versa if a failure is unrecognizable the value of Cd_m can be increased.

The first and second column describe the categories and criteria used in the risk matrix of Vlisco. The third column gives an explanation of how the criterion is incorporated in the mathematical model. Table 12 shows that all criteria but repair time are considered in the mathematical model.

6.5 Implementation into software.

Since manually solving would take too much effort, software is needed to solve the mixed integer linear programming (MILP) model above. First solving the model in Microsoft Excel was attempted since it is used a lot at Maintenance Vlisco. However, the mathematical model was too complex to be solved in Microsoft Excel. After considering a variety of options the software program Gusek was found suitable to implement the mathematical model. Gusek is a free software program that supports solving large scale linear programming models. The type of programming language used in Gusek is GNU Mathematical Programming Language (GMPL). The code of the mathematical model can be found in appendix H.

The input for the model is separately stored from the code. The data files that are used as input are in the format of Microsoft Excel spreadsheets. This facilitates a user friendly way of updating the data once new or more accurate data becomes available.

6.6 Chapter summary

In this chapter the mathematical model that will be used to answer the research questions was presented. The sets, parameters and variables were defined and the way the mathematical model works was described. The assumptions that were made related to the problem were also discussed. Furthermore a comparison with elements from the risk matrix and elements from the mathematical was made. Finally, it was discussed how the model will be implemented in software.

7. Verification and validation

It is important to verify if the model code in Gusek works as intended and if the results from the model are correct. Verification is making sure that the mathematical model has been correctly converted into a software program (Robinson, 1997). Validation is the art of ensuring that the developed model is accurate enough for the purpose at hand. Therefore, it is important to verify that the developed model represents the important elements of the real world problem that we are trying to solve.

7.1 Model verification

The software program Gusek has been used to code the model. Gusek has an integrated error handling system (debugging) that checks if any coding errors (bugs) have been made. The debugger checks if variables are properly defined and if any kind of syntax error is made. When a coding error is made the debugger gives an error message with the line number the error occurred. The model has been built in a systematic way using different modules. First the sets and parameters were defined. Next the decision variable and objective function were defined. Finally the constraints were added to the model. The verification of the code has been done by handling error messages of the debugger until no more errors occurred. Also, different tests with simple problem sets were performed to see if the model generated the optimal solution (see also: event validity tests in the next section).

7.2 Model validation

Now the mathematical model has been converted into a software program, it needs to be checked if the model accurately represents the real world and if the intended use of the model is ensured. To validate the model an event validity test, extreme condition test and a sensitivity analysis (Included in results, Chapter 8) have been performed.

Extreme condition tests

Extreme condition tests were performed on the input variables of the model. In none of the circumstances an error message occurred during the tests. Different scenarios with extreme costs (i.e costs of repair or downtime costs) were tested but each time the model came up with an optimal solution. When costs of repair were set to zero the model performed every maintenance job that was inserted. Vice versa, with very high costs (cost of repairs: 99 million) none of the repairs were performed. With either very high or low downtime costs the same pattern was observed.

Event validity tests

During the event validity tests the results from the model are compared with specific predefined events. These predefined events are basic in such a way that the solution is easy to calculate manually. The input of the tests is shown in Table 13 and Table 15, the output can be found in Table 14 and Table 16.

Table 13: Input of validity test of event 1.

Event 1					
Jobs	**Machine**	**Job description**	**Component**	**Repair costs**	**Time to failure**
	1	M1C1	1	10	0
	1	M1C2	2	1	1
	1	M1C3	3	5	2
Downtime costs	**Machines**	**Machine description**	**Downtime Costs**		
	1	M1	100		
Horizon	**Total Horizon**	**Total Budget**			
	3	10			

Table 14: Output of validity test of event 1.

Event 1				
Machine	**Component**	**Description**	**Performed**	
1	1	M1C1	1	
1	2	M1C2	0	
1	3	M1C3	0	
Total costs	**Repair costs**	**Downtime costs**		
210	10	200		
Machine	**Description**	**Downtime**	**Repair costs**	**Downtime costs**
1	M1	2	10	200
2	M2	0	0	0
3	M3	0	0	0

Table 15: Input of validity test of event 2.

Event 2					
Jobs	**Machine**	**Job description**	**Component**	**Repair costs**	**Time to failure**
	1	M1C1	1	5	0
	2	M2C1	1	5	0
	3	M3C1	1	5	0
Downtime costs	**Machines**	**Machine description**	**Downtime Costs**		
	1	M1	100		
	2	M2	300		
	3	M3	200		
Horizon	**Total Horizon**	**Total Budget**			
	3	10			

Table 16: Output of validity test of event 2.

Event 2				
Machine	**Component**	**Description**	**Performed**	
1	1	M1C1	0	
2	1	M2C1	1	
3	1	M3C1	1	
Total costs	**Repair costs**	**Downtime costs**		
310	10	300		
Machine	**Description**	**Downtime**	**Repair costs**	**Downtime costs**
1	M1	3	0	300
2	M2	0	5	0
3	M3	0	5	0

In the first situation (event 1) the maintenance jobs exist of three jobs, each at the same machine. Component 2 has a low cost of repair compared to the other components. The horizon is set to 3 periods and the total maintenance budget is 10. The downtime costs are set very high compared to the costs of repair. It is straightforward that component 1 will be the first candidate to be repaired since it fails the earliest from all components. Component 1 must be repaired since the costs of downtime are very high. After component 1 has been repaired there is no budget left for the other components (even though component 2 is very cheap to repair) to be repaired. Since the total horizon is 3 periods and component 2 fails in period 1, the total downtime is 2 periods, resulting in a total downtime cost of 200. The costs of repair were 10, which results in a total cost of 210. These costs are also found by the model in Gusek (see Table 14).

In the second situation (event 2) the maintenance jobs exist of three jobs, each at a different machine. The downtime cost of the machine is again very high compared to the repair cost of the components. This time the costs of repair are equal per component, but the downtime per machine is different. The budget is set to 10 and the costs of repair per component are 5 (so there is only budget for a maximum of two repairs). It is evident that the jobs with the highest associated downtime per machine should be performed. Machine 1 has the lowest downtime costs, so to keep the total costs at a minimum level this maintenance job should be skipped. Since every component fails from the start of the time horizon the total downtime costs are 300. The costs of repair are 10, resulting in a total cost of 310. Again, these costs are also found by the Gusek model in Gusek (see Table 16).

8. Results

Now the mathematical model has been verified and validated, the model can be run with the input provided by the maintenance engineers and maintenance manager of Vlisco. The input parameters that have been used can be found in Appendix E. The data consists of 128 maintenance jobs divided over 55 machines. The total time horizon is 36 months and the total maintenance budget that can be used is €5.320.000 (3 years, €1.660.000 + €1.660.000 + €2.000.000). The results of the model are summarized in Table 17. A full overview of the results can also be found in appendix F (Table 23).

Table 17: Results of mathematical model

Budget (€)	Budget (%)	Total costs (€)	Change (%)	Repair costs (€)	Change (%)	Downtime costs (€)	Change (%)
5.320.000	*100%*	6.703.200	-	5.292.000	-	1.411.200	-
3.724.000	*70%*	12.675.700	+89%	3.704.500	-30%	8.971.200	+536%
4.256.000	*80%*	10.100.900	+51%	4.254.500	-20%	5.846.400	+314%
4.788.000	*90%*	8.194.200	+22%	4.767.000	-10%	3.427.200	+143%
5.852.000	*110%*	5.991.100	-11%	5.789.500	+9%	201.600	-85%
6.384.000	*120%*	5.869.500	-12%	5.869.500	+11%	0	-100%
6.916.000	*130%*	5.869.500	-12%	5.869.500	+11%	0	-100%
6.916.000	*130%*	5.869.500	-12%	5.869.500	+11%	0	-100%

The first column gives the size of the maintenance budget that is used as input for the model. The second column describes the relative size of the budget compared to the budget used in the main solution. In the next columns the total costs are described and which part of these costs are repair costs or downtime costs. The column change (%) calculates the relative change compared to the main solution. For example, the change in total costs when the budget is cut to 70% of its original value is: $\left(\frac{12.675.700-6.703.200}{6.703.200}\right) * 100\ \% = 89\%$

As can be seen from the Table 17 the total estimated costs for 36 months are €6.703.200 of which €5.292.000 repair costs and €1.411.200 downtime (second row). Increasing the budget quickly leads to an estimated downtime cost of €0. Increasing the budget leads to a situation where the total leads to a minimum point of €5.869.500 (seventh row). Further increasing the maintenance budget will not lead to a lower total cost. Lowering the budget always leads to higher costs. When the budget is lowered by 10% the change in total costs is already significant, with an increase of 22% in costs (fifth row). Further decreasing the maintenance budget immensely increases the total costs, when the maintenance budget is cut to 70% of its original value the total costs are increased by 89% of which a 535% increase in downtime costs (third row).

A visual representation of the results is given in Figure 8 :

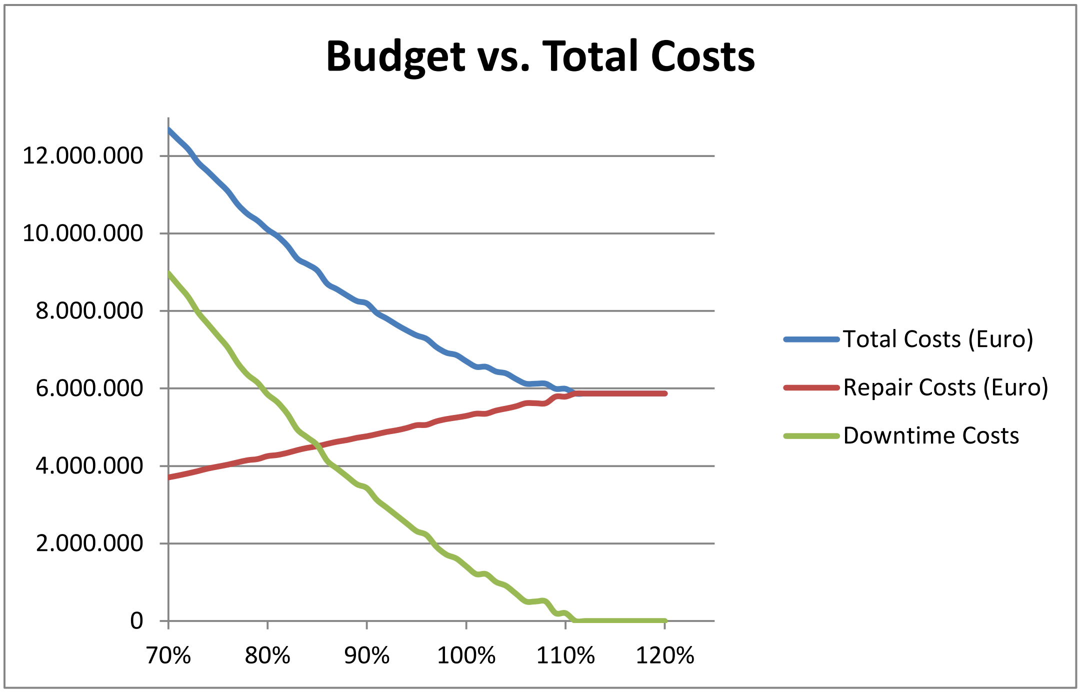


Figure 8: Total budget (%) plotted against the maintenance costs (€).

The graph above depicts the same situation as in Table 17. Increasing the budget leads to a reduction in costs to a maximum of €712.000 (€ 6.703.200 minus € 5.991.100). Decreasing the budget has poor consequences, represented by very high downtime costs when the maintenance budget is lower than the original maintenance budget.

Sensitivity analysis

Data extracted from the maintenance engineers of Vlisco is used as input for the mathematical model. If it is likely that some data are inaccurate, wrong or totally unavailable it is a good procedure to perform a sensitivity analysis (Robinson, 1997). With a sensitivity analysis the effect of any data inaccuracies can be identified. During a sensitivity analysis the input variables are modified and it is observed if the generated solution varies a lot or is stable. The sensitivity analysis has been conducted with the complete input data from Maintenance Vlisco for the years 2013 through 2015. The data consists of 128 maintenance jobs related to 55 machines with one or more components. The total horizon is 36 months and the maintenance budget is €5.320.000. The results of the different scenarios that have been tested are summarized in Table 18.

Table 18: Result of sensitivity analysis

Original situation			**Total costs**	**Repair costs**	**Downtime Costs**
Horizon	36		6.703.200	5.292.000	1.411.200
Budget	5.320.000				
Remaining life time of components	Original	*Absolute change*	0	0	0
Downtime costs per period	Original	*Relative change*	0%	0%	0%

Higher budget (+10%)					
Horizon	36		**Total costs**	**Repair costs**	**Downtime Costs**
Budget	5.852.000		5.991.100	5.789.500	201.600
Remaining life time of components	Original	*Absolute change*	-712.100	497.500	-1.209.600
Downtime costs per period	Original	*Relative change*	-11%	+9%	-85%
Lower budget (-10%)					
Horizon	36		**Total costs**	**Repair costs**	**Downtime Costs**
Budget	4.788.000		8.194.200	4.767.000	3.427.200
Remaining life time of components	Original	*Absolute change*	1.491.000	-525.000	2.016.000
Downtime costs per period	Original	*Relative change*	+22%	-9%	+142%
Increased remaining life time (+10%)					
Horizon	36		**Total costs**	**Repair costs**	**Downtime Costs**
Budget	5.320.000		5.997.600	5.292.000	705.600
Remaining life time of components	+10%	*Absolute change*	-705.600	0	-705.600
Downtime costs per period	Original	*Relative change*	-10%	+0%	-50%
Decreased remaining life time (-10%)					
Horizon	36		**Total costs**	**Repair costs**	**Downtime Costs**
Budget	5.320.000		7.207.900	5.309.500	1.898.400
Remaining life time of components	-10%	*Absolute change*	504.700	17.500	487.200
Downtime costs per period	Original	*Relative change*	+7%	+0,3%	+34%
Increased downtime costs (+10%)					
Horizon	36		**Total costs**	**Repair costs**	**Downtime Costs**
Budget	5.320.000		6.844.320	5.292.000	1.552.320
Remaining life time of components	Original	*Absolute change*	141.120	0	141.120
Downtime costs per period	+10%	*Relative change*	+2%	+0%	10%
Decreased downtime costs (10%)					
Horizon	36		**Total costs**	**Repair costs**	**Downtime Costs**
Budget	5.320.000		6.562.080	5.292.000	1.270.080
Remaining life time of components	Original	*Absolute change*	-141.120	0	-141.120
Downtime costs per period	-10%	*Relative change*	-2%	+0%	-10%

In the first two columns the situation that is analyzed is summarized, it contains the value of the parameters that are used. The difference for each situation is written in bold letters. The last three columns provide the output of the model given the situation. It provides, the total costs, repair costs and downtime costs respectively. The absolute change describes the difference in total costs between the original and new situation.
The relative change is a comparison with the original situation (a budget of €5.320.000) expressed as a percentage.

As can be seen from the table above, changes in the input have quite a significant impact on the output. When increasing the budget by 10% the downtime costs lower by 85% resulting in a total cost reduction of 10%. Lowering the budget has an even more severe impact on the total costs. A budget decrease of 10% leads to an increase of 142% in total downtime costs resulting in a total cost increase of 22%. When the lifetime of components is either increased or decreased by 10% the total costs lower by 10% or increase by 7% respectively. The change in input parameters for the downtime costs have a straightforward influence on the output. When downtime costs of the machines are increased or decreased the total downtime costs increase with exactly the same percentage.

Because the output varies a lot based on the input it is important that the input parameters are estimated as well as possible.

9. Answers to the research questions
In this chapter the answers are given to the research questions that were formulated in section 2.1.

9.1 Answer to the main research question
The main research question was:

1. *Taking into account budget restrictions, when to perform which preventive replacement on which production facilities to achieve the highest possible performance (in terms of money) for Vlisco?*

The answer to the main research question follows from the result of the mathematical model. The model determines for each specified maintenance job if the maintenance job should be performed or not. The question of when to perform the maintenance job depends on the estimation that is given by the maintenance engineers for the time to failure of each component of a machine. If a job is performed it is always at the same moment as the estimated time to failure. The model only takes the situation into account where budget can be freely spent over the total time horizon. Including a restriction on the amount of money that can be spent per period will very likely lead to a situation worse than the situation described in chapter 8.

9.2 Answers to the remaining research questions
The second research question was:

2. *Is the current method that is used to select the most risky facilities correct?*

The mathematical model contains all the important elements to answer the research question. The multiple machines and its components of Vlisco can be inserted into the model together with the parameters (repair costs, time to failure and downtime costs) that were considered important. Before, mainly subjective discussions with the risk matrix of Vlisco used as support were used in the decision of performing maintenance. The developed mathematical model provides an objective way in the decision of performing or not performing a certain maintenance job. A comparison with the elements in the risk matrix of Vlisco and how these elements return in the mathematical model was also made (section 6.4, Table 12).

The way of thinking and methods used of Vlisco seems correct, all but one criteria of the risk matrix is seen back in the mathematical model. The risk matrix of Vlisco is fairly subjective. The method of determining the most risky facilities is improved in a more objective way by using the mathematical model.

The third research question was:

3. *What are the consequences for Vlisco as a whole if the maintenance budget is increased (or decreased)?*

As described in chapter 8, the current situation leads to a total cost of €6.703.200, of which €5.292.000 are repair costs and €1.411.200 downtime costs. Based on the mathematical model this situation is almost optimal. When the maintenance budget is increased the total costs can go down to a minimum of €5.869.500 of which all repair costs. Decreasing the maintenance budget would be very risky, since a 10% budget decrease would already lead to 22% higher total costs.

At present time the maintenance budget seems to be at an acceptable size. Based on the results of the model a larger maintenance budget leads to lower total costs. By increasing the budget, the total reduction in costs that can be achieved is 12% (see Table 17). The implications of a smaller budget are a lot worse. Decreasing the budget by 10% already leads to a big increase in total costs (22%) due to a 143% increase in downtime costs.

At the moment increasing the maintenance budget is always worth because of the high downtime costs compared to the costs of repair. The same phenomenon is observed in the form used by finance (section 4.4) that maintenance needs to use to receive funds for maintenance activities. The total risk limitation expressed in euros calculated in the form is always way higher than the costs of repair.

10. Conclusions and recommendations

For this master thesis project a mathematical model has been developed to aid Maintenance Vlisco in the decision of when to perform which maintenance job. The mathematical model is the first objective step that calculates the effects of a limited maintenance budget for Vlisco.

In the mathematical model the maintenance budget could be spent at any time and was not restricted per period. As discussed in section 4.4, the maintenance budget for Vlisco is preferably the same each month, so that approximately each month the same amount of money is spent. This implementation of this additional restriction would have significant consequences on the mathematical model. Without budget restrictions per period the maintenance budget can be freely spent. If the amount is restricted per period situations could occur where money is needed to perform a maintenance job but the money is not available. This means that the maintenance job has to be performed either earlier or at a later point in time (or not at all, but this is also the case when budget can be freely spent). This extra restriction will always lead to the same or a worse situation than when budget can be freely spent. Therefore, only the situation where budget can be freely spent was analyzed.

The risk matrix appears to be a good foundation in the selection of most risky facilities. All criteria except one can be found back in one way or another in the mathematical model. The risk matrix of Vlisco can still be used to map the most risky facilities. The human role plays a big part in the maintenance strategy of Vlisco. The condition of machines is manually monitored by the people on the work floor. The risk matrix of Vlisco helps the maintenance department to stay informed about the condition of the machine park. Together with the developed mathematical model more objective maintenance decisions can be made on which maintenance job to perform or not. The model is a next step in the realization process of Vlisco of what affects the decision process in performing certain maintenance jobs.

10.1 Implementation into company.

After completing the tool, the tool including how to use, was presented to the maintenance engineers, maintenance manager and financial business controller of Vlisco. The maintenance engineers will be the people who will mostly use the tool. The people felt that the mathematical model added value to their decision process of which maintenance activity to perform. The idea of quantifying downtime costs is still relatively new at Maintenance Vlisco. Reactions were that the model raised their awareness of which costs are of importance in the decision of which maintenance job to perform.

Before only the cost of performing the maintenance job itself were taken into account. Furthermore, the consequences (risks) of performing or not performing a maintenance job were on qualitative grounds. The model helped the maintenance engineers to quantify the consequences in terms of costs.

The model is expected to run on any computer available at Vlisco. The model was tested on the oldest systems that are still in use by some of the employees at Vlisco (system specifications: Intel Core 2 Duo, 2.40GHZ, 2048MB RAM). The run time of the model on this type of system was at most 8 seconds.

The tutorial on how to use the tool can also be found in appendix D.

10.2 Recommendations for Maintenance Vlisco

The data used as input for the model is based on the experience of the maintenance engineers and / or maintenance manager (and not on real failure data), which makes it more likely that the input data can contain inaccuracies. Furthermore, the mathematical model developed in this research is based on several assumptions that simplify the real world. Therefore it is recommended to not blindly follow the results of the model. The results of the model should be taken into consideration as an additional theoretical foundation in the decision of performing a certain maintenance job or not. The model shows that downtime costs play a big part in the decision of performing a maintenance job or not. By adjusting different input paramaters, especially the size of the maintenance budget, the influence of the size of the maintenance budget on the total costs can be determined. The results of the model can then be used as an extra argument for Maintenance Vlisco to obtain budget from the finance department. In summary, the following recommendatoins are made:

- In combination with the current methods of Maintenance Vlisco the model can be used to support the decisions about which maintenance activities to perform to keep costs at a minimum level.
- Results from the model can be used to strengthen the position of the maintenance department to get funding for the most important maintenance activities.
- Input data does not seem that accurate at the moment. Many components of the same machine with an equal time to failure. Also downtime costs are a rough estimate only consisting of four levels. The sensitivity analysis in chapter 8 showed that variation in the input can vary the output by quite a bit. It is recommended that the input data is estimated as well as possible.
- The risk matrix of Vlisco is an ongoing development process. As discussed in section 4.2 Vlisco is still working on further developing the risk matrix by including the new criteria: product polarization, utilization rate, minimal buffer capacity and redundancy. Product polarization takes into account the difference in value of products that can be produced. These are elements that can be used in future research for Vlisco in the improvement of the mathematical model in this research.

- In today’s environment, situations may change quickly. For example, if the demand in the product of Vlisco suddenly drops causing a way lower utilization rate of the machines the costs of downtime can become a lot lower. Costs of downtime can greatly affect the decision in performing or not performing a maintenance job. Therefore it is recommended that the input used in the model should be in accordance with the latest insights available.

10.3 Limitations of the research

Below limitatoins related to the research problem and suggestions for further research are summarized:

- Increasing the maintenance budget is always valuable because of the high downtime costs. When the maintenance budget is increased sufficiently, a situation is reached where the downtime costs equal €0. In the real world, due to uncertainty the downtime costs will probably never reach €0. But it still shows that increasing the maintenance budget can have very positive consequences.
- The component life is based on an estimate of the maintenance engineers. If the input is based on actual historic data it might be a lot more accurate. Due to the time constraint of this research it was not tested what the exact effects are for Vlisco with more precise data. The sensitivty analysis in chapter 8 showed the influence of variation in the input paramaters.
- The component life is determinisitic, if maintenance jobs are not performed, the failure rate does not increase, while this would be expected in a real world. If accurate failure data would come available at Maintenance Vlisco it can be interesting to do more research and develop a similar model that uses stochastic distributions (i.e. weibull) to make it represent reality more.

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Appendix A List of Abbreviations

CBM: Condition based maintenance

GMPL: GNU Mathematical Programming Language

KPI: Key performance indicator

MDT: Mean down time

MILP: Mixed integer linear programming

MTBF: Mean time between failure

MTTF: Mean time to failure

MTTR: Mean time to repair

OEE: Overall Equipment Effectiveness

Appendix B Glossary of terms

Alternative machines: Term used by maintenance Vlisco to indicate if other machines exist that can perform the same job.

Availability: The percentage of time the production facility is performing its intended function. (For Maintenance Vlisco: the actual production time divided by the scheduled production time).

Chain effect: Term used in the risk matrix of Vlisco, it estimates the influence of a failed machine on the rest of the machines in the production chain.

Chance of failure: Term used in the risk matrix of Vlisco, it is an estimate of time (in years) until a big (worst possible scenario) failure occurs on a machine.

Component: A part of a machine of the larger whole. All components together form a machine.

Criticality (matrix): A table developed by Maintenance Vlisco to identify the production facilities that are the most at risk.

Detectability: Term used in the risk matrix of Vlisco, it estimates the extent to which failures can be detected in time.

Downtime: Time during which a machine is unable to perform its intended function.

Facilities: The whole chain of machines that are used in the production process of Vlisco.

GNU Mathematical Programming Language: A modeling language that can be used to make linear mathematical programming models.

Hardware risk: Term used in the risk matrix of Vlisco, it measured the maintainability of the hardware used in the machines of Vlisco.

Knowledge risk: Term used in the risk matrix of Vlisco, it measures to what extend the knowledge about machines is still available among the staff of Vlisco.

Machine: A device consisting of several parts, performing a particular task in the production chain. The term machine is used to identify a single production device in the total production chain of Vlisco.

Machine coordinator: Person that is responsible for a machine. The machine coordinator provides assistance to the machine operators, and is always up to date with the state of the machine he or she is responsible for.

Machine operator: Person who is in charge for the control of a machine. The machine operator ensures that the production runs as smooth as possible.

Operating risk: Term used in the risk matrix of Vlisco, it measures the maintainability of the steering mechanism that is used for a machine.

Production leader: Person that is responsible for the production line.

Reliability: The probability that a system will perform its required function for a specified period of time under a given set of operating conditions

Repair time: The time it takes for a machine to be repaired.

Total scheduled production time: The total time during a day that a machine is scheduled for production. The planning department makes estimates on how much time is needed on a machine to process a production order. These times are used to make a production planning.

Appendix C ROI model on cost savings

This appendix provides the ROI sheet that is used by maintenance to get funding for maintenance.

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Figure 9 : The ROI model on cost savings

Appendix D Tutorial: How to use the tool

This section describes how to use the tool that is developed in the software program Gusek.

Figure 10 gives a schematic overview of the tool. The oval boxes display the content of the in- and output that is used in the model. The document shapes represent the data files that are used with the model. And the square represents the Gusek model itself.

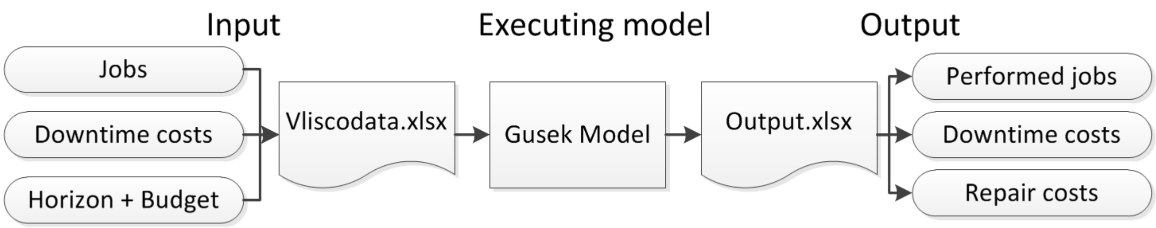


Figure 10: Overview of the tool.

Starting Gusek

The model files are provided in the file VliscoModel.zip. It both includes the executable program Gusek and the model file. To install the model the only thing that needs to be done is to extract the file VliscoModel.zip. To run Gusek open the file gusek.exe. The following screen as depicted in Figure 11 will pop up:

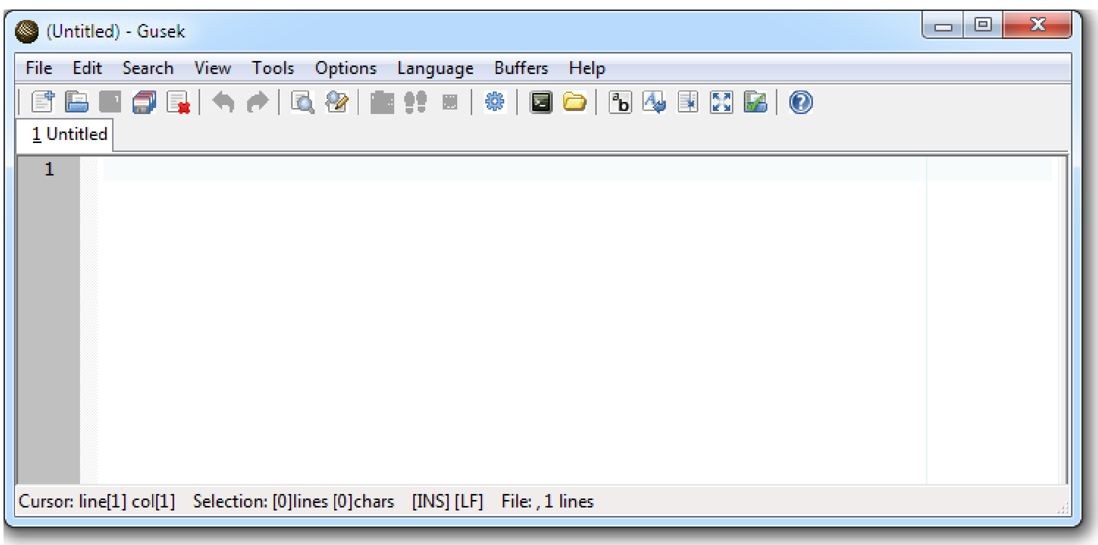


Figure 11: The main screen of Gusek.

To import the model click: File → Open and select the file Vliscomodel.mod. The following screen will appear (Figure 12):

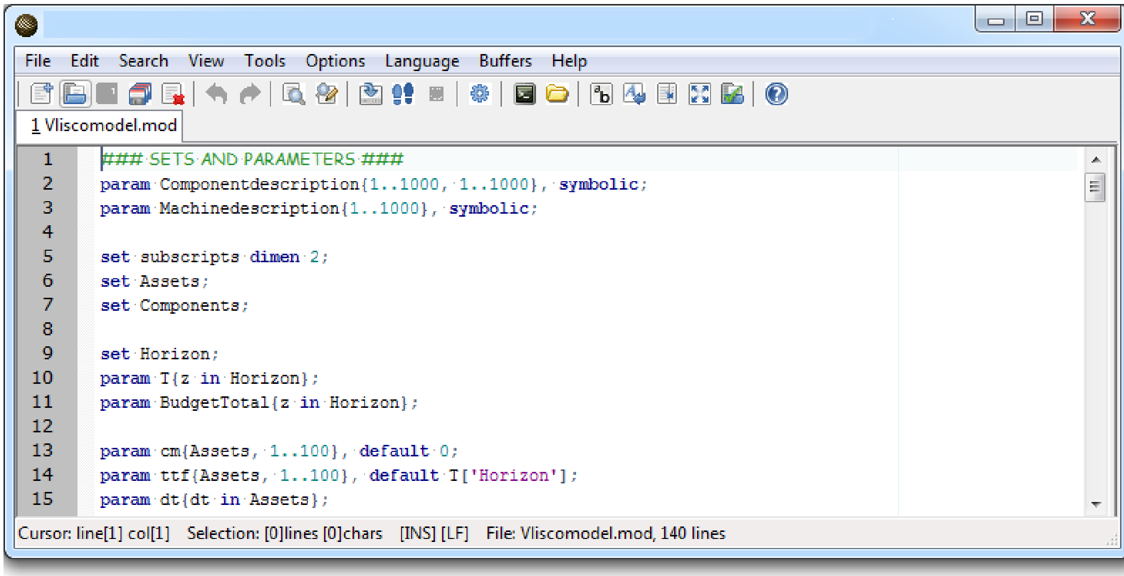


Figure 12: Gusek screen when the Vliscomodel has been opened.

Running the model

The model is run by clicking on the go command in the software program Gusek as depicted in Figure 13. An alternative way of running the model is using the menu via Tools and then clicking Go.

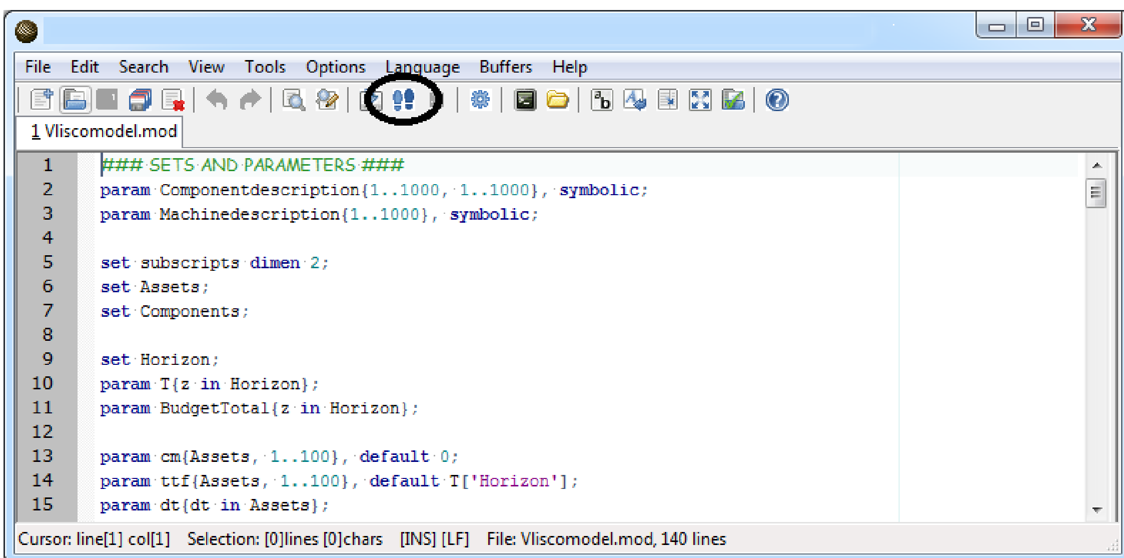
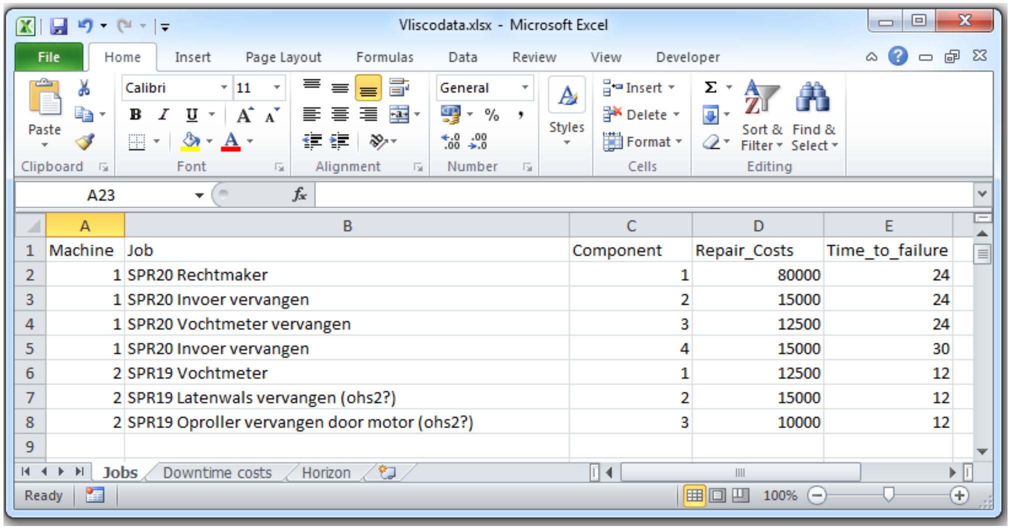


Figure 13: Running the model in Gusek.

Input

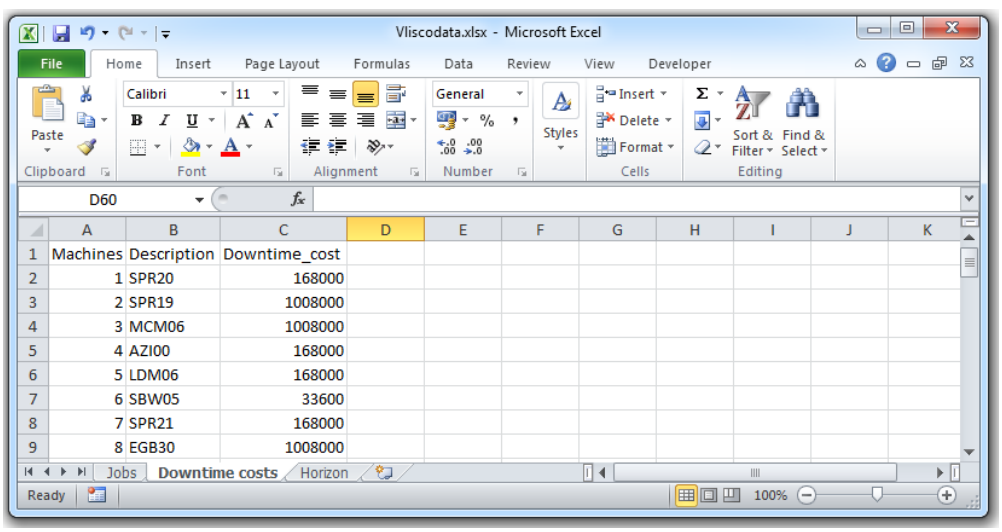
The input of the model works via Excel files and is separated from the programming code. The input data is stored into the file Vliscodata.xlsx. Figure 14 shows the tab where the maintenance jobs are defined. For each maintenance job a machine number (column 1) and a component number is defined (column 3) together with a description of the maintenance job (column 2). In the fourth column the repair costs (€) are stated and in the fifth column the time to failure (in periods, in this case months) is defined. It is important to note that the times to failure of the components for each machine must be in order of lowest to highest time to failure .



Machine	Job	Component	Repair_Costs	Time_to_failure
1	SPR20 Rechtmaker	1	80000	24
1	SPR20 Invoer vervangen	2	15000	24
1	SPR20 Vochtmeter vervangen	3	12500	24
1	SPR20 Invoer vervangen	4	15000	30
2	SPR19 Vochtmeter	1	12500	12
2	SPR19 Latenwals vervangen (ohs2?)	2	15000	12
2	SPR19 Oproller vervangen door motor (ohs2?)	3	10000	12

Figure 14: Excel tab where the maintenance jobs are defined.

In the second tab the downtime costs (€) per period (month) are defined for each machine, as shown in Figure 15. The first column describes the machine number, the second column gives a description of the machine and the third column gives the downtime cost for this machine (€).



Machines	Description	Downtime_cost
1	SPR20	168000
2	SPR19	1008000
3	MCM06	1008000
4	AZI00	168000
5	LDM06	168000
6	SBW05	33600
7	SPR21	168000
8	EGB30	1008000

Figure 15: Excel tab with parameters for machine downtime costs.

In the third and last tab the total time horizon (months) is set, together with its associated maintenance budget, as shown in Figure 16 .

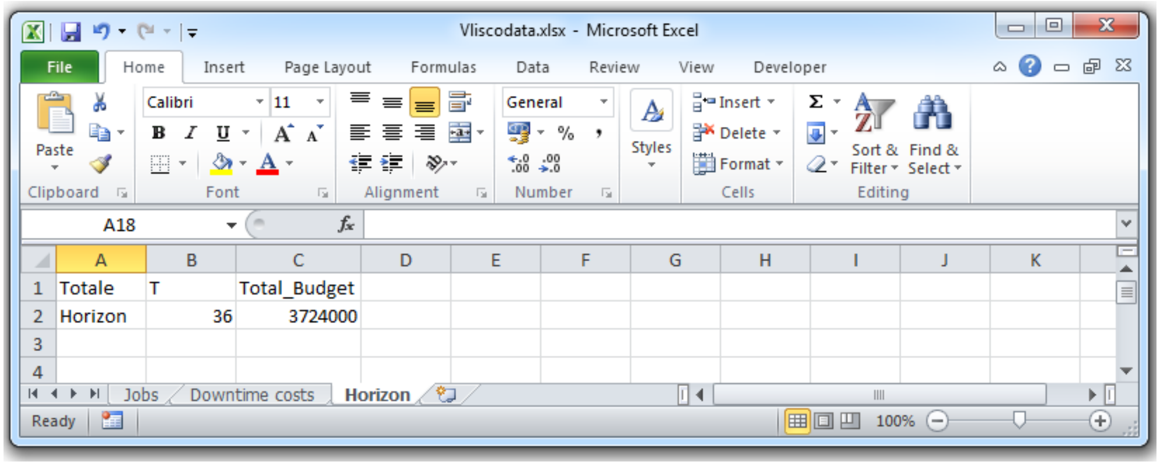


Figure 16: Excel tab where the total time horizon and the total budget is defined.

In the second column the total time horizon in periods is given. In the third column the total budget (€) for this total time horizon is given. The first column is not used as input, but is still needed for the model to extract the data from Excel.

Editing the input

Editing the input is done by changing the input parameters in the three different excel tabs as described in the section above. Adding a maintenance job can be done by adding a new row in the Excel tab Jobs. This is done by selecting a row, then pressing the right mouse button and clicking "insert" (Dutch: Invoegen), see Figure 17. The machine number that goes with the component replacement should be given in the first column. In the second column a description of the job must be given. In third column the component number must be given. If it is the first job for a machine, the component number that must be entered is 1, if it is the second maintenance job, number 2 must be entered and so on. In the fourth column the costs (€) of executing the maintenance job must be given. In the fifth column the time to failure of the machine component must be entered (in periods). Note: Do not change the name of the headings in row 1.

In the second Excel tab, the downtime costs per period (€) for each machine that is used in the first excel tab (Jobs) must be given. In the first column the machine numbers should be entered. The machine numbers in the downtime costs tab should correspond with the machine numbers in the Jobs tab. Or vice versa, the machine numbers used in the jobs tab should correspond with the machine numbers used in the downtime costs tab. Note: Again, do not change the name of the headings in row 1.

The total time horizon can be edited in the third Excel tab called horizon. The only two cells that can be edited here are B2 and C2. In the second column the total time horizon in periods can be changed by modifying the parameter value in cell B2. In the third

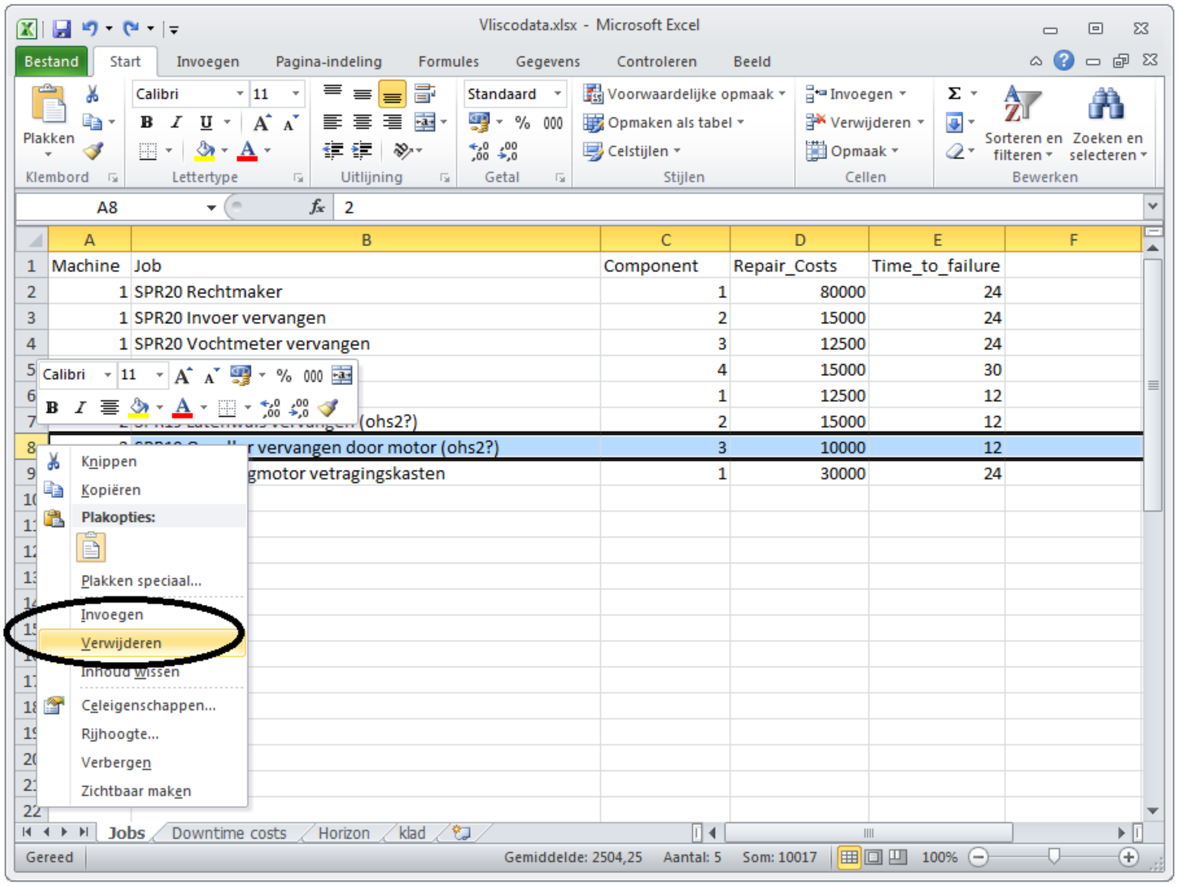


Figure 17: Inserting or deleting a new row in the excel tab Jobs.

column, the total budget that can be spent can be modified in cell C2. Note: Again, do not change the headers in row 1 and also do not change the text fields in column 1.

Once all parameters are set to the right values the model can be run by executing the go command in Gusek. This will create the output files as described below.

Output

The output of the model is exported and stored in the Excel file Output.xlsx. If the output file is opened while running the model it will display in the upper right corner if the model is still calculating, when finished the model will display the word 'ready' in green letters. Figure 18 shows a situation where the model is still calculating and Figure 19 shows when the calculation has been finished.

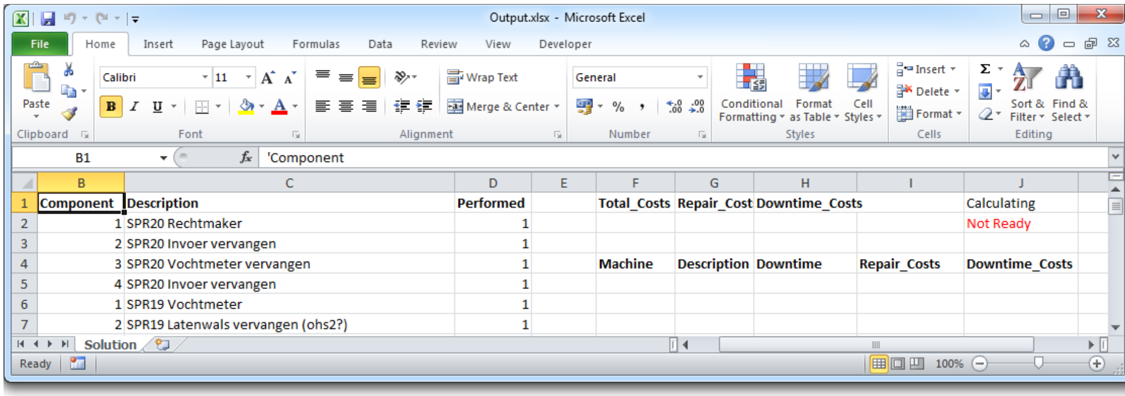


Figure 18: Output file when model is still calculating.

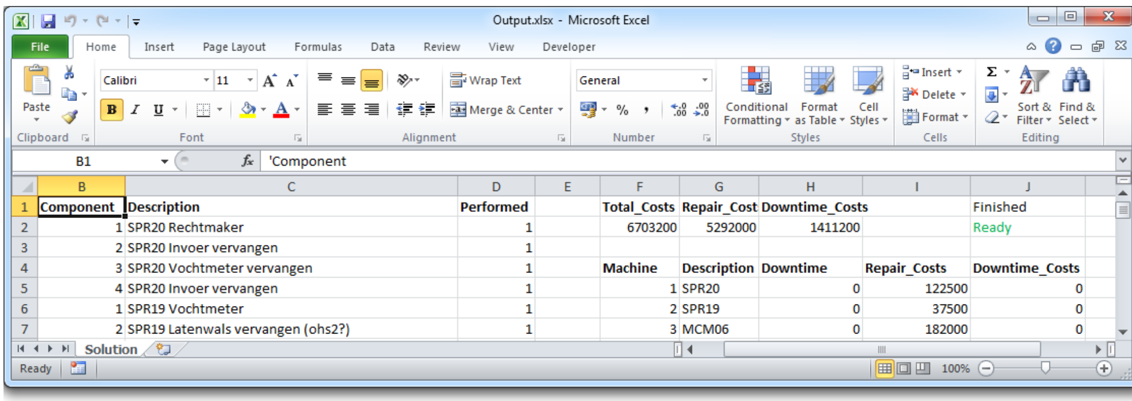


Figure 19: Output file when model has finished the calculations.

When the model is finished calculating, it is recommended to save the results under a different filename. This can be done by clicking File and then Save as (Dutch: Bestand followed by Opslaan als).

Appendix E Data Input for mathematical model

Below in Table 19, Table 20 and Table 21 the parameter values used as input for the model to generate the results of chapter 8 are displayed.

Table 19: Content of the tab Jobs from the data input file.

Machine	Job	Component	Repair_Costs (€)	Time_to_failure (periods)
1	SPR20 Rechtmaker	1	80000	24
1	SPR20 Invoer vervangen	2	15000	24
1	SPR20 Vochtmeter vervangen	3	12500	24
1	SPR20 Invoer vervangen	4	15000	30
2	SPR19 Vochtmeter	1	12500	12
2	SPR19 Latenwals vervangen (ohs2?)	2	15000	12
2	SPR19 Oproller vervangen door motor (ohs2?)	3	10000	12
3	MCM06 Kettingmotor vetragingskasten	1	30000	24
3	MCM06 Scutcher Aanvoer baan verlengen	2	30000	30
3	MCM06 Afzuiging	3	12000	30
3	MCM06 Besturing	4	50000	30
3	MCM06 Pompen	5	60000	30
4	AZI00 Operationeel onderhouden	1	60000	12
4	AZI Vervangen scada	2	14000	12
5	LDM06 Harsbakken	1	5000	24
5	LDM06 Aandrijving pas en meetsysteem	2	20000	24
5	LDM06 Wals	3	35000	30
5	LDM06 Afzuiging	4	20000	30
5	LDM06 Afwikkelaar	5	10000	30
5	LDM06 Lustermangel	6	7500	30
6	SBW05 Slopen, besturing / utilities	1	60000	24
7	SPR21 Invoer vervangen	1	15000	18
7	SPR21 Invoer vervangen	2	15000	24
7	SPR21 Vochtmeter vervangen	3	12500	24
8	EGB30 Pekelkelder coaten	1	26000	30
9	OHS02 Aandrijving	1	200000	12
9	OHS02 Gasinstallatie	2	100000	12
9	OHS02 Constructie Zeepbak	3	50000	12
9	OHS02 Ketting SPR19	4	100000	12
9	OHS02 E-kast SBW03	5	150000	12
9	OHS02 Besturing S5	6	100000	12
9	OHS02 SPR19 Invoer vervangen	7	150000	12
9	OHS02 Aandrijving PSM01/02	8	100000	12
9	OHS02 Tribak	9	150000	12
10	HTA10 Breekwaterfiltratie afsluiters vervangen	1	15000	24

11	LWB01 Tri detectie / scada emissie	1	25000	30
11	LWB01 FID meting centraal maken	2	40000	30
12	EGB00 Luchtlekkage reduceren	1	10000	30
12	EGB00 Modificatie	2	20000	30
12	EGB00 Onderstation	3	20000	36
12	EGB00 Distributienet	4	20000	36
12	EGB00 Onderstation	5	30000	36
13	EGB50 Zandfilter	1	20000	12
13	EGB50 Zandfilter 2	2	20000	24
13	EGB50 Zandfilter 3	3	20000	12
14	ZWF03 Bodem verstevigen	1	20000	30
14	ZWF03 Aandrijving	2	60000	30
15	EGB60 BG gebouw noord vervangen	1	35000	30
15	EGB60 BG 1e gebouw noord vervangen leidingdeel	2	20000	30
15	EGB60 EB kunstof leiding	3	85000	30
15	EGB60 Rak oost kleurhuis 1 op 1 vervangen	4	65000	30
15	EGB60 Chem.eiland	5	15000	30
15	EGB60 HTA (verdieping 1, 2 en 3)	6	80000	30
15	EGB60 Gebouw VE (centrale werkplaats)	7	6000	30
15	EGB60 Gebouw VN (LDM06, HDMI en GRV)	8	25000	30
15	EGB60 Rak Oost	9	9000	30
15	EGB60 Energie bedrijf Zandfilters)	10	22000	30
15	EGB60 Rak west (SBW05)	11	3000	30
15	EGB60 BG gebouw noord	12	65000	30
15	EGB60 Gebouw Noord BG 1 2 3	13	90000	30
16	GIP01 vervangen scada	1	30000	36
16	GIP01 Gasregeling	2	100000	36
17	GIP02 vervangen scada	1	30000	30
18	GIP03 vervangen scada	1	30000	30
18	GIP03 Gearbox	2	50000	30
19	HTA00 vervangen scada	1	60000	24
20	ZWF01 Vocht meter vervangen	1	12500	30
20	ZWF01 Branders	2	25000	30
21	OHS03 Vervangen Scada	1	25000	12
21	OHS03 Saneren	2	20000	12
22	SBV01 Aandrijving	1	100000	12
22	SBV01 Reserve unit reviseren	2	20000	12
22	SBV01 Verfbak	3	40000	12
23	WJM01 Waxjetmachine vervangen	1	300000	24
23	WJM01 Waxjetmachine spareparts	2	40000	24
24	BAK05 Brander vervangen	1	130000	12

24	BAK05 Aandrijving vervangen	2	100000	12
25	BLK00 J-Boxen	1	60000	36
25	BLK00 Witte aflegger	2	30000	36
26	DGP01 Plaatsnijderij vervanger	1	100000	12
27	GWR01 Regeling	1	30000	30
28	GWR02 Regeling	1	30000	30
29	HDM05 Koers	1	15000	24
30	IVM03 Compensator	1	20000	30
30	IVM03 Perswerk	2	20000	30
30	IVM03 zinkstukkenketting	3	10000	30
30	IVM03 Bagger afvoerbak	4	7500	30
31	IVM04 Polenketting	1	10000	24
31	IVM04 Zinkstukkenketting	2	5000	24
31	IVM04 Compensator	3	20000	24
31	IVM04 Perswerk	4	20000	24
32	IVM06 Besturingen	1	85000	24
32	IVM06 Compensator	2	20000	24
32	IVM06 Perswerk	3	20000	24
32	IVM06 Zinkstukkenketting	4	5000	24
32	IVM06 Doekinloop	5	15000	24
32	IVM06 Bagger afvoerbak	6	7500	24
32	IVM06 Upgrade	7	100000	24
33	IVM08 Optimalisatie	1	20000	30
34	KSM01 Aandrijving	1	80000	30
35	LMM04 Optimalisatie	1	20000	30
36	RSM01 Slijpmachine	1	100000	24
37	SBW06 Schutcher	1	140000	24
38	STO20 Tracing	1	25000	30
38	STO20 Aandrijving	2	60000	30
39	VSM02 Baan sturing	1	15000	12
39	VSM02 Constructie	2	45000	12
40	WOP01 Vervangen	1	25000	24
41	BRW07 Branders	1	20000	24
41	BRW07 Afzuiging	2	50000	24
41	BRW07 Mangel	3	50000	24
42	EGB20 Linda	1	50000	30
43	EGB40 Ketel 24	1	2000000	36
44	HDMI05 Mangels	1	80000	24
44	HDMI05 Deuren bediening	2	30000	24
44	HDMI05 Besturing	3	80000	24
45	IJS01 Besturing	1	20000	24

46	ROL12 Aandrijving	1	90000	30
46	ROL12 Kroonwiel	2	100000	30
47	SPR22 Aandrijving	1	200000	30
48	SPR23 Aandrijving	1	250000	30
49	VEB15 Aandrijving	1	20000	30
50	VEB16 Aandrijving	1	20000	30
51	VLG00 Middenhoogspanning	1	100000	36
52	ZWF02 Branders	1	25000	24
53	WIM04 Modomix	1	140000	30
54	YST01 Pompsysteem	1	30000	30
55	ZNG01 Branders	1	50000	24

Table 20: Content of the tab Downtime from the data input file.

Machines	Description	Downtime_cost (€)
1	SPR20	168000
2	SPR19	1008000
3	MCM06	1008000
4	AZI00	168000
5	LDM06	168000
6	SBW05	33600
7	SPR21	168000
8	EGB30	1008000
9	OHS02	1008000
10	HTA10	1008000
11	LWB01	1008000
12	EGB00	1008000
13	EGB50	168000
14	ZWF03	84000
15	EGB60	1008000
16	GIP01	1008000
17	GIP02	33600
18	GIP03	33600
19	HTA00	1008000
20	ZWF01	84000
21	OHS03	33600
22	SBV01	33600
23	WJM01	168000
24	BAK05	33600
25	BLK00	168000
26	DGP01	168000
27	GWR01	168000

28	GWR02	84000
29	HDM05	168000
30	IVM03	33600
31	IVM04	84000
32	IVM06	84000
33	IMV08	33600
34	KSM01	84000
35	LMM04	84000
36	RSM01	33600
37	SBW06	1008000
38	STO20	84000
39	VSM02	1008000
40	WOP01	33600
41	BRW07	168000
42	EGB20	168000
43	EGB40	1008000
44	HDMI05	168000
45	IJS01	84000
46	ROL12	84000
47	SPR22	168000
48	SPR23	84000
49	VEB15	33600
50	VEB16	33600
51	VLG00	168000
52	ZWF02	84000
53	WIM04	84000
54	YST01	33600
55	ZNG01	168000

Table 21: Content of the tab Horizon from the data input file.

Total	T (periods)	Total_Budget (€)
Horizon	36	5320000

Appendix F Data output from mathematical model

Below in Table 22 the output of the mathematical model is displayed. The input from this run is the data provided in Appendix E.

Table 22: Output after running the mathematical model.

Machine	Component	Description	Performed (1=yes, 2=no)		Total_Costs (€)	Repair_Costs (€)	Downtime_Costs (€)		Finished
1	1	SPR20 Rechtmaker	1		6703200	5292000	1411200		Ready
1	2	SPR20 Invoer vervangen	1						
1	3	SPR20 Vochtmeter vervangen	1		**Machine**	**Description**	**Downtime (periods)**	**Repair _Costs (€)**	**Downtime_Costs (€)**
1	4	SPR20 Invoer vervangen	1		1	SPR20	0	122500	0
2	1	SPR19 Vochtmeter	1		2	SPR19	0	37500	0
2	2	SPR19 Latenwals vervangen (ohs2?)	1		3	MCM06	0	182000	0
2	3	SPR19 Oproller vervangen door motor (ohs2?)	1		4	AZI00	0	74000	0
3	1	MCM06 Kettingmotor vetragingskasten	1		5	LDM06	0	97500	0
3	2	MCM06 Scutcher Aanvoer baan verlengen	1		6	SBW05	0	60000	0
3	3	MCM06 Afzuiging	1		7	SPR21	0	42500	0
3	4	MCM06 Besturing	1		8	EGB30	0	26000	0
3	5	MCM06 Pompen	1		9	OHS02	0	1100000	0
4	1	AZI00 Operationeel onderhouden	1		10	HTA10	0	15000	0
4	2	AZI Vervangen scada	1		11	LWB01	0	65000	0
5	1	LDM06 Harsbakken	1		12	EGB00	0	30000	0
5	2	LDM06 Aandrijving pas en meetsysteem	1		13	EGB50	0	60000	0
5	3	LDM06 Wals	1		14	ZWF03	0	80000	0
5	4	LDM06 Afzuiging	1		15	EGB60	0	520000	0
5	5	LDM06 Afwikkelaar	1		16	GIP01	0	0	0
5	6	LDM06 Lustermangel	1		17	GIP02	0	30000	0
6	1	SBW05 Slopen, besturing / utilities	1		18	GIP03	6	0	201600
7	1	SPR21 Invoer vervangen	1		19	HTA00	0	60000	0
7	2	SPR21 Invoer vervangen	1		20	ZWF01	0	37500	0
7	3	SPR21 Vochtmeter vervangen	1		21	OHS03	0	45000	0
8	1	EGB30 Pekelkelder coaten	1		22	SBV01	0	160000	0
9	1	OHS02 Aandrijving	1		23	WJM01	0	340000	0
9	2	OHS02 Gasinstallatie	1		24	BAK05	0	230000	0
9	3	OHS02 Constructie Zeepbak	1		25	BLK00	0	0	0
9	4	OHS02 Ketting SPR19	1		26	DGP01	0	100000	0
9	5	OHS02 E-kast SBW03	1		27	GWR01	0	30000	0
9	6	OHS02 Besturing S5	1		28	GWR02	0	30000	0

9	7	OHS02 SPR19 Invoer vervangen	1		29	HDM05	0	15000	0
9	8	OHS02 Aandrijving PSM01/02	1		30	IVM03	6	0	201600
9	9	OHS02 Tribak	1		31	IVM04	0	55000	0
10	1	HTA10 Breekwaterfiltratie afsluiters vervangen	1		32	IVM06	0	252500	0
11	1	LWB01 Tri detectie / scada emissie	1		33	IMV08	0	20000	0
11	2	LWB01 FID meting centraal maken	1		34	KSM01	0	80000	0
12	1	EGB00 Luchtlekkage reduceren	1		35	LMM04	0	20000	0
12	2	EGB00 Modificatie	1		36	RSM01	0	100000	0
12	3	EGB00 Onderstation	0		37	SBW06	0	140000	0
12	4	EGB00 Distributienet	0		38	STO20	0	85000	0
12	5	EGB00 Onderstation	0		39	VSM02	0	60000	0
13	1	EGB50 Zandfilter	1		40	WOP01	0	25000	0
13	2	EGB50 Zandfilter 2	1		41	BRW07	0	120000	0
13	3	EGB50 Zandfilter 3	1		42	EGB20	0	50000	0
14	1	ZWF03 Bodem verstevigen	1		43	EGB40	0	0	0
14	2	ZWF03 Aandrijving	1		44	HDMI05	0	190000	0
15	1	EGB60 BG gebouw noord vervangen	1		45	IJS01	0	20000	0
15	2	EGB60 BG 1e gebouw noord vervangen leidingdeel	1		46	ROL12	6	0	504000
15	3	EGB60 EB kunstof leiding	1		47	SPR22	0	200000	0
15	4	EGB60 Rak oost kleurhuis 1 op 1 vervangen	1		48	SPR23	6	0	504000
15	5	EGB60 Chem.eiland	1		49	VEB15	0	20000	0
15	6	EGB60 HTA (verdieping 1, 2 en 3)	1		50	VEB16	0	20000	0
15	7	EGB60 Gebouw VE (centrale werkplaats)	1		51	VLG00	0	0	0
15	8	EGB60 Gebouw VN (LDM06, HDMI en GRV)	1		52	ZWF02	0	25000	0
15	9	EGB60 Rak Oost	1		53	WIM04	0	140000	0
15	10	EGB60 Energie bedrijf Zandfilters)	1		54	YST01	0	30000	0
15	11	EGB60 Rak west (SBW05)	1		55	ZNG01	0	50000	0
15	12	EGB60 BG gebouw noord	1						
15	13	EGB60 Gebouw Noord BG 1 2 3	1						
16	1	GIP01 vervangen scada	0						
16	2	GIP01 Gasregeling	0						
17	1	GIP02 vervangen scada	1						
18	1	GIP03 vervangen scada	0						
18	2	GIP03 Gearbox	0						
19	1	HTA00 vervangen scada	1						
20	1	ZWF01 Vocht meter vervangen	1						
20	2	ZWF01 Branders	1						
21	1	OHS03 Vervangen Scada	1						

21	2	OHS03 Saneren	1						
22	1	SBV01 Aandrijving	1						
22	2	SBV01 Reserve unit reviseren	1						
22	3	SBV01 Verfbak	1						
23	1	WJM01 Waxjetmachine vervangen	1						
23	2	WJM01 Waxjetmachine spareparts	1						
24	1	BAK05 Brander vervangen	1						
24	2	BAK05 Aandrijving vervangen	1						
25	1	BLK00 J-Boxen	0						
25	2	BLK00 Witte aflegger	0						
26	1	DGP01 Plaatsnijderij vervanger	1						
27	1	GWR01 Regeling	1						
28	1	GWR02 Regeling	1						
29	1	HDM05 Koers	1						
30	1	IVM03 Compensator	0						
30	2	IVM03 Perswerk	0						
30	3	IVM03 zinkstukkenketting	0						
30	4	IVM03 Bagger afvoerbak	0						
31	1	IVM04 Polenketting	1						
31	2	IVM04 Zinkstukkenketting	1						
31	3	IVM04 Compensator	1						
31	4	IVM04 Perswerk	1						
32	1	IVM06 Besturingen	1						
32	2	IVM06 Compensator	1						
32	3	IVM06 Perswerk	1						
32	4	IVM06 Zinkstukkenketting	1						
32	5	IVM06 Doekinloop	1						
32	6	IVM06 Bagger afvoerbak	1						
32	7	IVM06 Upgrade	1						
33	1	IVM08 Optimalisatie	1						
34	1	KSM01 Aandrijving	1						
35	1	LMM04 Optimalisatie	1						
36	1	RSM01 Slijpmachine	1						
37	1	SBW06 Schutcher	1						
38	1	STO20 Tracing	1						
38	2	STO20 Aandrijving	1						
39	1	VSM02 Baan sturing	1						
39	2	VSM02 Constructie	1						
40	1	WOP01 Vervangen	1						
41	1	BRW07 Branders	1						
41	2	BRW07 Afzuiging	1						

41	3	BRW07 Mangel	1						
42	1	EGB20 Linda	1						
43	1	EGB40 Ketel 24	0						
44	1	HDMI05 Mangels	1						
44	2	HDMI05 Deuren bediening	1						
44	3	HDMI05 Besturing	1						
45	1	IJS01 Besturing	1						
46	1	ROL12 Aandrijving	0						
46	2	ROL12 Kroonwiel	0						
47	1	SPR22 Aandrijving	1						
48	1	SPR23 Aandrijving	0						
49	1	VEB15 Aandrijving	1						
50	1	VEB16 Aandrijving	1						
51	1	VLG00 Middenhoogspanning	0						
52	1	ZWF02 Branders	1						
53	1	WIM04 Modomix	1						
54	1	YST01 Pompsysteem	1						
55	1	ZNG01 Branders	1						

Table 23: Model results given different sizes of the maintenance budget.

Budget	Budget (%)	Total costs	Change (%)	Repair costs	Change (%)	Downtime costs	Change (%)
3.724.000	*70%*	12.675.700	89%	3704500	-30%	8.971.200	536%
3.777.200	*71%*	12.423.300	85%	3754500	-29%	8.668.800	514%
3.830.400	*72%*	12.175.900	82%	3809500	-28%	8.366.400	493%
3.883.600	*73%*	11.832.700	77%	3869500	-27%	7.963.200	464%
3.936.800	*74%*	11.595.300	73%	3934500	-26%	7.660.800	443%
3.990.000	*75%*	11.342.900	69%	3984500	-25%	7.358.400	421%
4.043.200	*76%*	11.090.500	65%	4034500	-24%	7.056.000	400%
4096400	*77%*	10747300	60%	4094500	-23%	6652800	371%
4149600	*78%*	10499900	57%	4149500	-22%	6350400	350%
4202800	*79%*	10328300	54%	4179500	-21%	6148800	336%
4256000	*80%*	10100900	51%	4254500	-20%	5846400	314%
4309200	*81%*	9929300	48%	4284500	-19%	5644800	300%
4362400	*82%*	9681900	44%	4339500	-18%	5342400	279%
4415600	*83%*	9348700	39%	4409500	-17%	4939200	250%
4468800	*84%*	9204600	37%	4467000	-16%	4737600	236%
4522000	*85%*	9045500	35%	4509500	-15%	4536000	221%
4575200	*86%*	8702300	30%	4569500	-14%	4132800	193%
4628400	*87%*	8558200	28%	4627000	-13%	3931200	179%
4681600	*88%*	8399100	25%	4669500	-12%	3729600	164%
4734800	*89%*	8255000	23%	4727000	-11%	3528000	150%

4788000	*90%*	8194200	22%	4767000	-10%	3427200	143%
4841200	*91%*	7946800	19%	4822000	-9%	3124800	121%
4894400	*92%*	7802700	16%	4879500	-8%	2923200	107%
4947600	*93%*	7643600	14%	4922000	-7%	2721600	93%
5000800	*94%*	7499500	12%	4979500	-6%	2520000	79%
5054000	*95%*	7370400	10%	5052000	-5%	2318400	64%
5107200	*96%*	7279600	9%	5062000	-4%	2217600	57%
5160400	*97%*	7067200	5%	5152000	-3%	1915200	36%
5213600	*98%*	6923100	3%	5209500	-2%	1713600	21%
5266800	*99%*	6862300	2%	5249500	-1%	1612800	14%
5320000	*100%*	6703200	0%	5292000	0%	1411200	0%
5373200	*101%*	6559100	-2%	5349500	1%	1209600	-14%
5426400	*102%*	6559100	-2%	5349500	1%	1209600	-14%
5479600	*103%*	6437500	-4%	5429500	3%	1008000	-29%
5532800	*104%*	6389200	-5%	5482000	4%	907200	-36%
5586000	*105%*	6245100	-7%	5539500	5%	705600	-50%
5639200	*106%*	6123500	-9%	5619500	6%	504000	-64%
5692400	*107%*	6123500	-9%	5619500	6%	504000	-64%
5745600	*108%*	6123500	-9%	5619500	6%	504000	-64%
5798800	*109%*	5991100	-11%	5789500	9%	201600	-86%
5852000	*110%*	5991100	-11%	5789500	9%	201600	-86%
5905200	*111%*	5869500	-12%	5869500	11%	0	-100%
5958400	*112%*	5869500	-12%	5869500	11%	0	-100%
6011600	*113%*	5869500	-12%	5869500	11%	0	-100%
6064800	*114%*	5869500	-12%	5869500	11%	0	-100%
6118000	*115%*	5869500	-12%	5869500	11%	0	-100%
6171200	*116%*	5869500	-12%	5869500	11%	0	-100%
6224400	*117%*	5869500	-12%	5869500	11%	0	-100%
6277600	*118%*	5869500	-12%	5869500	11%	0	-100%
6330800	*119%*	5869500	-12%	5869500	11%	0	-100%
6384000	*120%*	5869500	-12%	5869500	11%	0	-100%
6437200	*121%*	5869500	-12%	5869500	11%	0	-100%
6490400	*122%*	5869500	-12%	5869500	11%	0	-100%
6543600	*123%*	5869500	-12%	5869500	11%	0	-100%
6596800	*124%*	5869500	-12%	5869500	11%	0	-100%
6650000	*125%*	5869500	-12%	5869500	11%	0	-100%
6703200	*126%*	5869500	-12%	5869500	11%	0	-100%
6756400	*127%*	5869500	-12%	5869500	11%	0	-100%
6809600	*128%*	5869500	-12%	5869500	11%	0	-100%
6862800	*129%*	5869500	-12%	5869500	11%	0	-100%
6916000	*130%*	5869500	-12%	5869500	11%	0	-100%

Appendix G Explanation of downtime formula

Recalling form section 6.3 the objective function used to minimize the total relevant cost is:

$$\sum_{m=1}^{M}\left(\sum_{c_m=1}^{C_m}[(T-L_{mc_m})-(T-L_{mc_{m+1}})](1-X_{mc_m})\right)*CD_m+\sum_{m=1}^{m}\left(\sum_{c_m=1}^{C_m}X_{mc_m}*C_{m_{cm}}\right)$$

The first part of the formula (between the brackets) is where the total downtime for a machine is calculated:

$$\sum_{c_m=1}^{C_m}[(T-L_{mc_m})-(T-L_{mc_{m+1}})](1-X_{mc_m})$$

Here an example is given of how this formula works. Assume the following parameter settings:

$L_{11}=2$
$L_{12}=5$
$T=6$
$L_{13}=6$ (This follows from restriction 5 in the model formulation (see section 6.3)

The data above describes one machine with two components (So $C_1=2$). The first component fails after 2 periods and the second component fails after 5 periods. The total time horizon is 6 periods.

The following three results may come from the model:

1. $X_{11}=0$ and $X_{12}=0$
2. $X_{11}=1$ and $X_{12}=0$
3. $X_{11}=1$ and $X_{12}=1$

The results where $X_{11}=0$ and $X_{12}=1$, is not possible due to restriction 4 in the model formulation (see section 6.3). Component repairs must be performed in order of remaining life time (from lowest to highest). Component one either fails first or at the same time as component two. So if component one is not repaired it would never be optimal to repair component two for the same machine.

Filling in the downtime formula we get:

- Result 1

$[(6-2)-(6-5)](1-0)+[(6-5)-(6-6)](1-0)=3+1=4$

- Result 2

$$[(6-2)-(6-5)](1-1)+[(6-5)-(6-6)](1-0)=0+1=1$$

- Result 3

$$[(6-2)-(6-5)](1-1)+[(6-5)-(6-6)](1-1)=0+0=0$$

As can be seen from the calculations above the downtimes are indeed correct. If none of the components are repaired the machine will fail after 2 periods (this is the time to failure of the component one). Since the total time horizon is 6 periods the total downtime will be 4 periods.

If only component one is repaired the machine will fail at the time to failure of component 2. The time to failure of component 2 was 5 periods. Since the total time horizon is 6 periods, the total downtime will be 1 period.

If both components are repaired the machine will not fail at all during the total time horizon. This indeed results in a total downtime of 0 periods.

Appendix H Gusek code

This appendix provides the GNU Mathematical Programming Language (GMPL) code that was used in combination with the software program Gusek to solve the mathematical model.

```
### SETS AND PARAMETERS ###
param Componentdescription{1..1000, 1..1000}, symbolic;
param Machinedescription{1..1000}, symbolic;

set subscripts dimen 2;
set Assets;
set Components;

set Horizon;
param T{z in Horizon};
param BudgetTotal{z in Horizon};

param cm{Assets, 1..100}, default 0;
param ttf{Assets, 1..100}, default T['Horizon'];
param dt{dt in Assets};

param Exceltable1, symbolic;
param Exceltable2, symbolic;
param Exceltable3, symbolic;
param Exceltable4, symbolic;
param Exceltable5, symbolic;
param Ready, symbolic;
param NotReady, symbolic;

### NOT READY EXCEL ###
table output {Ready} OUT "ODBC"
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm, *.xlsb)};' &
  'DBQ=.\Output.xlsx;READONLY=FALSE'
  'DROP TABLE [' & Exceltable4 & '];'
  'CREATE TABLE [' & Exceltable4 & ']'
  '("Calculating" STRING);'
  'INSERT INTO  [' & Exceltable4 & ']'
  '("Calculating")'
  'VALUES(?);' :
  NotReady;

### INPUT OF DATA VIA EXCEL ###
table input IN 'ODBC'
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm,
*.xlsb)};dbq=.\Vliscodata.xlsx'
'SELECT * FROM [Jobs$]'
:subscripts <- [Machine, Component], Componentdescription ~ Job, cm ~
Repair_Cost, ttf ~ Time_to_failure;

table input2 IN 'ODBC'
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm,
*.xlsb)};dbq=.\Vliscodata.xlsx'
'SELECT * FROM [Downtime Costs$]'
:Assets <- [Machine], Machinedescription ~ Description, dt ~
Downtime_cost;
```

```
table input3 IN 'ODBC'
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm,
*.xlsb)};dbq=.\Vliscodata.xlsx'
'SELECT * FROM [Horizon$]'
:Horizon <- [Totale], T ~ T, BudgetTotal ~ Total_Budget;

### (DECISION) VARIABLES ###
var x {i in 1..1000, j in 1..1000}, binary;

var one;

### OBJECTIVE ###
minimize totalcosts:
sum{a in Assets} ( sum{c in 1..100: cm[a,c] !=0} (
((T['Horizon'] - ttf[a,c]) - (T['Horizon'] - ttf[a,c+1])) * (one -
x[a,c]) ) * dt[a])
+
sum{a in Assets} ( sum{c in 1..100: cm[a,c] !=0} (
x[a,c] * cm[a,c]));

### CONSTRAINTS ###
subject to totalbudget:
sum {a in Assets} ( sum{c in 1..100: cm[a,c] !=0} ( x[a,c] * cm[a,c] )
) <= BudgetTotal['Horizon'];

subject to failorder {(a,c) in subscripts}:
x[a,c+1] <= x[a,c]  ;

subject to numberone: one = 1;

solve;

param downtimecosts := sum{a in Assets} ( sum{c in 1..100: cm[a,c] !=0}
(((T['Horizon'] - ttf[a,c]) - (T['Horizon'] - ttf[a,c+1])) * (one -
x[a,c]) ) * dt[a]);
param repaircosts := sum{a in Assets} ( sum{c in 1..100: cm[a,c] !=0}
(x[a,c] * cm[a,c]));

###OUTPUT FORMULATION###

table output {(a,c) in subscripts} OUT "ODBC"
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm, *.xlsb)};' &
  'DBQ=.\Output.xlsx;READONLY=FALSE'
  'DROP TABLE [' & Exceltable1 & '];'
  'CREATE TABLE [' & Exceltable1 & ']'
  '(Machine DOUBLE, Component DOUBLE, Description STRING, Performed
DOUBLE);'
  'INSERT INTO  [' & Exceltable1 & ']'
  '(Machine, Component, Description, Performed)'
  'VALUES(?, ?, ?, ?);' :
  a, c, Componentdescription[a,c], x[a,c];

table output {totalcosts} OUT "ODBC"
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm, *.xlsb)};' &
  'DBQ=.\Output.xlsx;READONLY=FALSE'
  'DROP TABLE [' & Exceltable2 & '];'
```

```
  'CREATE TABLE [' & Exceltable2 & ']'
  '(Total_Costs DOUBLE, Repair_Costs DOUBLE, Downtime_Costs DOUBLE);'
  'INSERT INTO  [' & Exceltable2 &']'
  '(Total_Costs, Repair_Costs, Downtime_Costs)'
  'VALUES(?, ?, ?);' :
  totalcosts, repaircosts, downtimecosts;

  table output {a in Assets} OUT "ODBC"
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm, *.xlsb)};' &
  'DBQ=.\Output.xlsx;READONLY=FALSE'
  'DROP TABLE [' & Exceltable3 & '];'
  'CREATE TABLE [' & Exceltable3 & ']'
  '(Machine DOUBLE, Description STRING, Downtime DOUBLE, Repair_Costs
DOUBLE, Downtime_Costs Double);'
  'INSERT INTO  [' & Exceltable3 &']'
  '(Machine, Description, Downtime, Repair_Costs, Downtime_Costs)'
  'VALUES(?, ?, ?, ?, ?);' :
  a, Machinedescription[a], sum{c in 1..100: cm[a,c] !=0} (
((T['Horizon'] - ttf[a,c]) - (T['Horizon'] - ttf[a,c+1])) * (one -
x[a,c]) ), sum{c in 1..100: cm[a,c] !=0} (
x[a,c] * cm[a,c]), sum{c in 1..100: cm[a,c] !=0} (
((T['Horizon'] - ttf[a,c]) - (T['Horizon'] - ttf[a,c+1])) * (one -
x[a,c]) ) * dt[a];

  table output {Ready} OUT "ODBC"
  'DRIVER={Microsoft Excel Driver (*.xls, *.xlsx, *.xlsm, *.xlsb)};' &
  'DBQ=.\Output.xlsx;READONLY=FALSE'
  'DROP TABLE [' & Exceltable4 & '];'
  'CREATE TABLE [' & Exceltable4 & ']'
  '(Finished STRING);'
  'INSERT INTO  [' & Exceltable4 & ']'
  '(Finished)'
  'VALUES(?);' :
  Ready;

data;

param Exceltable1 := 'TabelEen';
param Exceltable2 := 'TabelTwee';
param Exceltable3 := 'TabelDrie';
param Exceltable4 := 'TabelVier';
param Exceltable5 := 'TabelVijf';
param NotReady :='Not Ready';
param Ready :='Ready';

end;
```