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# Analysing the cost-effectiveness of predictive maintenance programs using a simulation cost model

A case study for the vacuum compressor pumps at Duyvis


TU Delft

Duyvis

# Analysing the cost-effectiveness of predictive maintenance programs using a simulation cost model

## A case study for the vacuum compressor pumps at Duyvis


By

L. P. Mars


## Master Thesis

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TU Delft

# Preface

With this thesis, I complete my master Multi-Machine Engineering (MME) at the technical university in Delft. Although I have always said that I would never do anything with machines, it has happened. I did my thesis as an assignment for the vacuum compressor pumps of Duyvis.

During the assignment, my interest in maintenance at production sites grew enormously. This is due to the fantastic atmosphere within Duyvis, I was involved in everything and encouraged to look around.

During my thesis, several people shared their experiences and knowledge. I would like to thank these people. The insights gained have contributed to the quality of this research.

I would also like to thank my supervisor at Duyvis, Jan Droog. Jan has ensured that I immediately felt at home within Duyvis, and that while I worked mainly at home. Through our weekly 'even bijpraten' meetings, I was able to get an idea of what was going on within the factory. In addition, Jan has fully involved me in the developments and decisions made regarding the predictive maintenance policy, which was helpful for the project and has encouraged me to continue in the field of maintenance. Due to all these aspects, my time at Duyvis was informative, a lot of fun and tasty.

Besides Jan, I would also like to thank my supervisor from the TU, Yusong Pang. For being critical but positive during our meetings, for setting deadlines so that I can actually achieve this final result, and for keeping his patience when we discussed my research questions for the umpteenth time. I also would like to thank Dingena Schott for being critical but supportive in during the meetings.

Finally, I would like to thank my friends and family for their support. I would especially like to thank my housemates for their confidence in me at all times, the much-needed distraction, and especially Pien for her artistic capabilities. I would like to thank my mother and Sander for their unconditional trust, even though I know that it was difficult to understand exactly what I was doing. Last but not least, I would like to thank Maarten for the distraction that was needed to focus entirely on my research again, from the beers at the Doerak to weekend get-aways, it was all very helpful.

I hope you will enjoy reading my thesis.

Laura Mars
Delft, November 2021

# Summary

In this thesis, a simulation cost model is developed. The simulation cost model will be used to analyse the cost-effectiveness of predictive maintenance programs. The research will be conducted as a case study for the vacuum compressor pumps at Duyvis.

Over the years, there has been a growing interest in predictive maintenance (PdM). PdM is a maintenance policy that uses the condition of the asset to plan the maintenance actions. Due to this, PdM can be very beneficial when it is applied correctly. This is where the problem starts. Because in line with the increase in interest, there has also been an increase in PdM program options. A PdM program can be applied in various ways but are in general classified according to maturity levels. This research will focus on applications of 3 maturity levels, which are [23]:

- **Level 2:** Periodic inspections performed using an instrument. (Discontinuous)
- **Level 3:** Real-time online condition monitoring of the asset. (Continuous)
- **Level 3 plus:** Combination of inspections with instrument and online condition monitoring, combination of level 2 and 3. (Continuous)

The different maturity levels have different program options. Due to the large number of options available, it is difficult for maintenance departments to select the most suited option for their situation. Currently, the literature only focuses on maintenance strategy or policy selection. There is a lack of tool that can provide information on the application of the selected policy. This gap in the literature will partially be closed by developing a simulation tool that can assist in selecting a PdM program.

To do this, a case study at Duyvis is conducted. Duyvis wants to enhance their PdM program, but they want to make a well-informed decision. Currently, they have a level 2 PdM program which is executed by the service partner Facta. By adjusting the PdM program, they want to be more cost-effective. The application of the PdM program is adjusted, or there is an increase in the maturity level. This research for Duyvis will focus on the vacuum compressor pumps. The pumps are a critical asset because a failure will reduce the production capacity by 60%. Also, selecting a PdM program for this asset is difficult due to the discontinuous operating profile.

To structure the research the following main research question is answered.
***How can predictive maintenance be applied in the most cost-effective way to the vacuum compressor pumps at Duyvis.***

To answer this question, first, some general information on the application of PdM in practice is provided. To start, maintenance actions are the actions taken with the intention to restore the asset so that it can perform its function [3]. To structure the maintenance actions, the use is made of a maintenance strategy, which is built up of maintenance policies. In the literature, three main maintenance policies are presented, corrective, preventive and predictive maintenance. As already presented, this thesis will focus on PdM. PdM is applied using a PdM program which consists of 3 main parts [16, 32]:

1. **Data Acquisition:** Gathering data of the asset.
2. **Data Processing:** Analysing the data to give insight in the condition of the asset
3. **Decision making:** Using the information on the condition of the asset to determine how the maintenance actions should be planned.

A PdM program can be classified according to 4 maturity levels [23]. The main difference between the maturity levels is how the data is collected, resulting in discontinuous and continuous programs. Currently, most PdM programs are at a level 2, but companies are looking into ways to enhance their application.

Using this information, it is time to zoom in to the case study by selecting the focus point of the PdM program. This thesis will focus on the vacuum compressor pumps at Duyvis. At Duyvis 4 vacuum compressor pumps are used for flour transport. They are critical assets, have a discontinuous operating profile, and generally fail due to blockage or bearing failure. In this research, the focus of the PdM program will be bearing failure. Bearing failure tends to evolve over 4 different stages. The different stages indicated the severity of the damage, which can be related to a certain amount of life left. Also, the different stages give insight in the way the maintenance actions should be planned. In figure 1, a schematic representation of the different stages of bearing damage is presented.

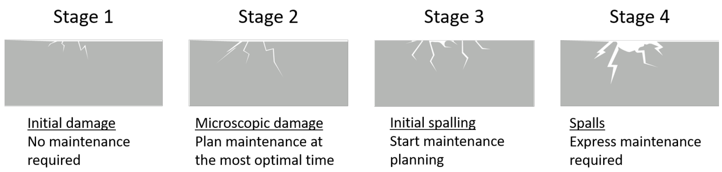


Figure 1: Stages bearing damage

Besides the focus point of the PdM program, a focus point for the selection is set. The simulation cost model will be used to give insight in the cost-effectiveness of PdM programs. In this research, two KPIs are used to analyse the cost-effectiveness. **1) the overall cost**, focused on three categories, the cost related to the maintenance actions, the cost related to unplanned downtime and the cost related to the PdM program. The second KPI is **2) reliability**, is related to the number of unexpected breakdowns, the time available for maintenance planning and the way the maintenance actions are planned.

Using the focus point a selection can be made on the programs that could be applied to the vacuum compressor pumps. The decisions are related to the different parts of a PdM program.

1. **Data gathering:** The data is gathered using a condition monitoring technique. In this research, vibration analysis is selected. Vibration analysis looks at the change in the vibration pattern to detect damage. The data is gathered using an accelerometer.
2. **Data analysis:** The data is analysed using an analysing technique. The technique used depends on the configuration of the application and the frequency range of the sensor. The type of analysing technique used influences the ability to detect the different stages of bearing damage.
3. **Decision making:** In this research, 3 different planning options can be the result of the decision making, they are related to the stage of the damage at detection. These are: optimal planned maintenance (OPM), planned maintenance (PM) and express planned maintenance (EPM).

This information and requirements are used to narrow down the options for the vacuum compressor pumps. The main difference between the options are the maturity level, sample frequency and detectability. These aspects are difficult to determine and the simulation cost model will be used to analyse these aspects. The result is 5 programs, presented in table 1.

| Program | Name | Level | Sample frequency | Detect-ability* |
|---|---|---|---|---|
| 1 | Current situation | 2 | 3 to 4 Months | 1,2,3,4 |
| 2 | Quick Collect (QC) | 2 | 1 to 3 Months | 2,3,4 |
| 3 | SKF IMX1 | 3 | 3 hours | 2,3,4 |
| 4 | Banner | 3 | 5 min | 3,4 |
| 5 | QC+Banner | 3+ | 1-3Month/5 min | 2,3,4 |

* The ability to detect the 4 different stages of bearing damage.

Table 1: PdM programs

Program 1 is the current situation. Program 2 is a level 2 program where the inspections are performed in-house using the Quick Collect. Programs 3 and 4 are online continuous monitoring systems. Program 3 is supplied by SKF and is the IMx1. This system has a low sample frequency but a high detect-ability. Program 4 is supplied by Turck and is a Banner application. It has a higher sample frequency but lower detect-ability than program 3. Program 5 is a level 3 plus application and combines inspections using the Quick Collect with the Banner application, program 2 and program 4.

The cost effectiveness of these 5 programs will be analysed using the simulation cost model. The simulation cost model uses a discrete event simulation (DES) model in combination with a cost model. The interaction between the two models is presented in figure 2.

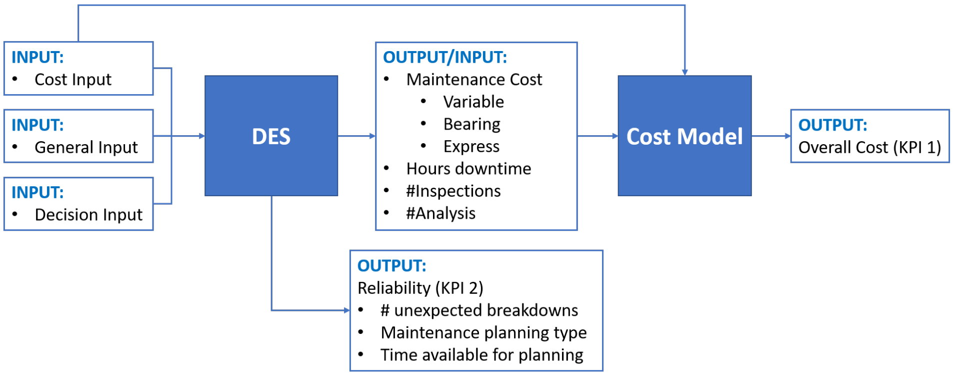


Figure 2: Overview simulation cost model

The DES model will be used to simulate the PdM program. This is, in short, done by selecting an end of lifetime (EoL) from a failure distribution. The machine will keep running unit the EoL is reached, resulting in an unexpected breakdown, or until interrupted. Interruption of the machine is the result of an alarm. The alarms are generated using the PdM program. The PdM program collects data, which will be used to determine the assets condition. This information is combined with alarm conditions to advise how the maintenance actions should be planned. The different planning options influence the cost model. The simulation will continue until the total simulation time is reached, 4 years.

There are two aspects of importance for the simulation cost model. These are the alarm conditions and the failure distribution. Firstly, the model works by using alarm conditions. A graphical presentation of the alarm conditions is presented in figure 3. The alarm conditions are related to the different stages of damage and the detect-ability of the PdM programs.

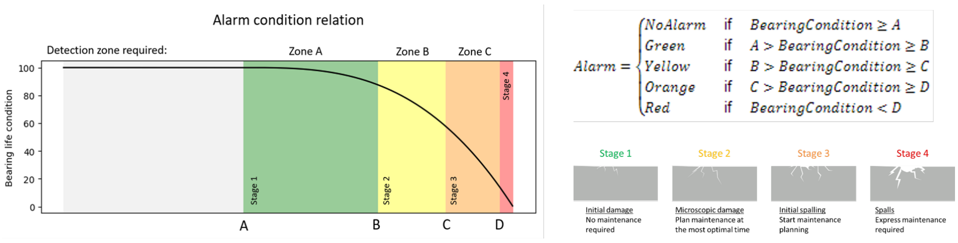


Figure 3: Relation alarm conditions

The second aspect of importance is the failure distribution. The failure distribution presents the probability the asset will fail at a certain time. Information provided by Atlas Copco is used to form a general failure distribution, presented in figure 4. The failure distribution consists of 1) Failures related to infant mortality, related to poor manufacturing. 2) Failures related to improper handling and maintenance, based on the guarantee period and 3) Failures due to old age, wear out. In this failure distribution the assumption is made that the probability the asset will fail within the simulation time of 4 years is 100%. The effect of other failure distribution on the outcome of the simulation model will be assessed.

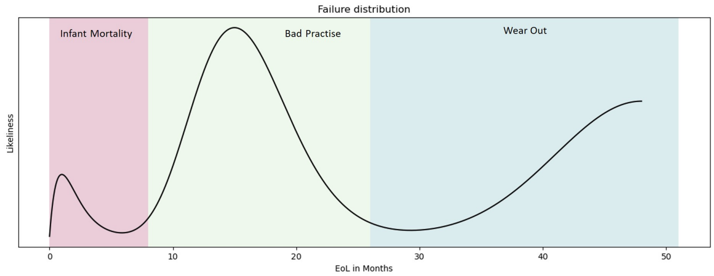


Figure 4: Failure distribution

The output of the DES model will give insight into the reliability, KPI 2, and will be used as input for the cost model. The cost model sums three cost aspects to determine the overall cost.

- **maintenance cost:** The cost related to the planning and executing of the maintenance actions. This is a fixed cost, the variable cost for secondary damage, the cost for the purchase of bearings, and express planning cost if required.
- **Downtime cost:** The cost related to unplanned downtime. Unplanned downtime will happen when the maintenance actions are not planned in time, and the asset will fail before the actions can begin. It is a function of the hours multiplied by a cost per hour.
- **PdM program cost:** Are the CAPEX and OPEX cost of the PdM program. The OPEX cost will focus on costs related to gathering and analysing the data.

The different PdM programs are analysed using the simulation cost model. To analyse the cost-effectiveness of the PdM programs, 2 KPIs are used, the overall cost and reliability. But throughout the research, it became clear that 4 aspects could influence the KPIs. These are: the alarm conditions, the failure distribution, the ON/OFF ratio of the asset and the inspection interval. 4 tests are conducted to analyse the effects of these influences on the outcome of the model.

**Test 1: Alarm conditions**
The alarm conditions used in the simulation cost model can be based on information found in the literature or used in practice. The effect this has on the outcome of the model will be analysed in this test. This test concludes that the different alarm conditions influence the reliability and thus the overall cost of the programs. Due to this, both alarm conditions are used to assess the cost-effectiveness.

**Test 2: Failure distribution**
There is much uncertainty about the exact failure distribution of the pumps. Due to this, 7 different failure distributions have been used to run the simulation. In general, the ratios between the options are similar, but one important aspect changes the outcome. The probability the asset will fail within the simulation time. If the asset does not fail, there are no benefits, only cost related to the program, which is unfavourable for the continuous programs. If the chance the asset will fail within the simulation time increases, the continuous programs become more cost-effective since the benefits start to play a role.

**Test 3: ON/OFF ratios**
The PdM program selected will be applied to 4 vacuum compressor pumps. The pumps are identical, but they have different operating profiles resulting in different ON/OFF ratios. Analysing the effect of the different ON/OFF ratios only showed change for PdM program 3. The reliability of program 3 is influenced by the different ON/OFF ratios. The extent depends on the alarm conditions.

**Test 4: Inspection Interval**
The discontinuous programs use inspections to gather the data. The frequency can easily be adjusted. The results of altering the inspection interval on the cost-effectiveness are as expected. Less time between the inspections will increase the reliability and reduce the cost. However, it is essential to take aspects not incorporated in the simulation cost model into account.

**Overall results: "Worst-case" scenario**
Besides the 4 tests also, a "worst-case" scenario is analysed. The "worst-case" scenario is built up using the information provided in the tests. The influences are selected as either being most likely or due to the highest effect. The alarm conditions are based on literature, the failure distribution is based on the information provided by Atlas Copco, the asset will 100% fail within the 4 years simulation time, the asset is 7,2% of the time ON and the inspection interval of program 1,2 and 5 are respectively, 4 , 2 and 4 months. Table 2 presents the results of the "worst case" situation,

| | Average cost per year [€] | Difference overall cost* | %UBD** | %EPM** | %PM** | %OPM** | TTP*** [weeks] |
|---|---|---|---|---|---|---|---|
| PdM 1 | 3911.1 | 0% | 49.5% | 55.6% | 18.7% | 25.7% | 1.9 |
| PdM 2 | 2790.3 | -31% | 22.4% | 43.3% | 7.1% | 49.6% | 5.8 |
| PdM 3 | 2359.8 | -40% | 3.7% | 18.9% | 5.9% | 75.1% | 6.3 |
| PdM 4 | 2203.4 | -44% | 0.0% | 18.6% | 81.4% | 0.0% | 4.4 |
| PdM 5 | 2187.4 | -44% | 0.0% | 18.3% | 57.6% | 24.1% | 5.1 |

* Is the difference in overall cost related to the current situation, a negative value represents a reduction in overall cost.
** UBD: Unexpected breakdown, EPM: express planned maintenance, PM: planned maintenance, OPM: optimal planned maintenance. The percentage indicate the occurrence of the maintenance type in the 500 repetitions.
*** TTP: Average time to plan the maintenance actions in weeks

Table 2: Numerical results "worst case" scenario

The table contains the average cost per year, the difference in overall cost related to the current situation, the percentage of unexpected breakdowns, similar for the other maintenance types and finally the average time to plan the maintenance actions.

Using the information provided in table 2 and the information gathered through the test shows that continuous programs are more cost-effective than discontinuous programs. This leaves programs 3, 4 and 5. These three options could all be cost-effective but there are some small difference that should be taken into account. PdM program 3, the IMx1 option, collects data every 3 hours. This in combination with the discontinuous operating profile of the vacuum pumps makes the IMx1 less robust. Since it is not always possible to detect damage in time using the IMx1, there is a small chance an unexpected breakdown might occur. PdM program 4 on the other hand has a higher sample frequency but is less reliable due to the inability to detect damage of stage 2, which results in less time to plan the maintenance actions.

So using this information, it can be concluded that the simulation cost model is able to give insight into the effect of the sample frequency and detect-ability of the programs on the cost-effectiveness. Also that out of the 5 different options, program 5 is the most cost-effective option for the vacuum compressor pumps in all situations. Applying PdM program 5 will result in an average cost reduction of 45% per year, and the average time to plan the maintenance actions will increase by 4 weeks. It should be noticed that this advise should be combined with other information and analysis, such as a SWOT analysis, to make a final selection on the program. This due to the fact that the simulation cost model only takes the detect-ability and the sample frequency of the programs into account.

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# 1
# Introduction

During the first industrial revolution, the steam engine was introduced. The second revolution drastically changed the way we organise manufacturing practices, introducing mass production and production lines. Automation was the result of the third industrial revolution. Automation was the result of the increase in options provided by computers and electronics. Currently, we are in the fourth industrial revolution, also called industry 4.0. Industry 4.0 uses cyber-physical systems that are connected through networks and the internet of things (IoT). These changes are applied to enhance the manufacturing practices even more.

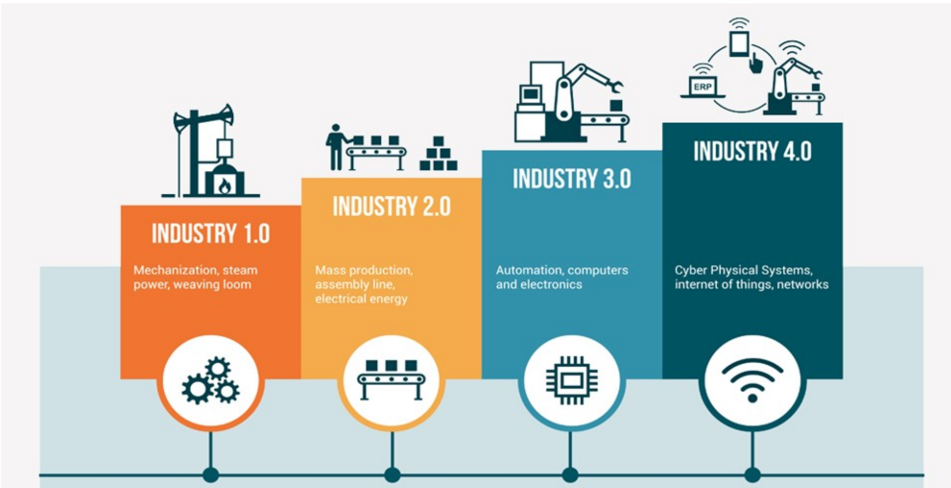



Figure 1.1: Industrial revolution [1]

In line with industry 3.0 and 4.0, the way companies view maintenance has changed. Maintenance is no longer viewed as an expense but is considered more positively as a profit centre. A well-selected maintenance strategy can play an essential role in keeping and improving the availability, product quality, safety requirements and operating cost levels of a production plant [44].

But what is maintenance? Maintenance is the activities that are taken with the intention to retain or restore an item or system to a state where it is able to perform its function [3]. The maintenance activities are structured using a maintenance strategy. As already mentioned, a well-selected maintenance strategy can reduce the overall maintenance cost. A maintenance strategy is in the paper by Shafiee and Sørensen [33] defined as: "a set of policies and actions that are used to "retain" or "restore" an equipment as well as the decision support system in which maintenance activities are planned".

Using the definition, it can be seen that a maintenance strategy is built-up of maintenance policies or a combination of policies. Originally there were two main maintenance policies, corrective and preventive. With a corrective maintenance policy, the maintenance activities are not planned but are performed when a failure has occurred [5]. A preventive maintenance policy does use a planning. The planning can be time, usage or calendar-based [45]. The maintenance activities are planned without the influence of the condition of the machine. Due to the developments in storing and analysing data related to industry 3.0 and 4.0, a new maintenance policy has emerged, predictive maintenance (PdM) [45]. PdM is a maintenance policy that uses data to determine the condition of the asset. The condition will be used to determine the best time to perform the maintenance actions.

A maintenance policy, and more specific, a PdM policy, is applied using a PdM program. A PdM program consists of three main parts, 1) data acquisition, 2) data processing, and 3) decision making. These three parts are all related to how the PdM program is applied and to what maturity level. In the research by Mulders and Haarman [23], 4 different maturity levels for PdM programs are introduced. The different maturity levels relate to the way the data is gathered, processed and how decisions are made. Besides the different maturity levels, the application of a PdM program is also very versatile. Currently, most companies have a level 2 or level 3 program and are looking to enhance their PdM policy. Either by moving up a maturity level or enhancing their application of the PdM program. In general, this is done by gathering enough data to implement a level 4 program eventually.

So, industrial revolutions have changed the way we manufacture our products and now has changed the way maintenance is viewed and how it can be applied. Due to the third and fourth industrial revolutions, we no longer see maintenance as an expense, and PdM's introduction results in more advanced options.

## 1.1. Duyvis

The same switch is happening at Duyvis. They are changing the way they look towards maintenance and are looking into cooperating more efficient PdM programs. Due to this, the research will be done as a case study for Duyvis. More on the research problem later, but first an introduction to Duyvis.

Duyvis is part of Pepsico and produces savoury peanut snacks. The snacks come in a variety of coatings and combinations. Their most famous product is the 'Borrelnootjes'. The snacks are produced and packaged at their production plant in Zaandam. The production runs 24/5. Production starts Sunday evening and stops on Friday morning. During the week, there are different types of peanut snacks produced and packaged.

Currently, Duyvis has a level 2 PdM program for their rotating assets. Similar to most companies in the industry, they are looking into ways to enhance their PdM program. They would like to do this by either enhancing the way their level 2 policy is applied or by increasing the maturity level.
The focus point for the PdM program will be the vacuum compressor pump. The vacuum compressor pump is a critical asset used at Duyvis for flour transport. The vacuum compressor pump has a discontinuous operating profile which makes it challenging to determine which PdM program will be able to detect the damage and is most cost-effective. Duyvis has 4 identical vacuum compressor pumps, and the selected PdM program has to be cost-effective for all 4 pumps.

## 1.2. Problem statement

As already presented, there has been an increase in interest in PdM. In line with this increase in interest, there has been an increase in PdM programs available on the market. This is where the problem starts. Due to the vars amount of PdM programs, selecting the best option for a distinct situation has become increasingly challenging. PdM programs come in a wide variety of applications and can be classified according to 4 maturity levels.

Currently, the literature focuses on the selection of maintenance strategies and policies, such as in the papers by Busse et al. [7], Gilabert et al. [11], Wolf et al. [45]. However, there is a lack of information on the selection of the most suited maintenance program. This gap in the literature will be partially closed in this research.

To do this, a case study is used, a cost-effective PdM program for Duyvis. Duyvis is experiencing the same problem. They want to improve their PdM program, but they want to make a well-informed decision. In this case study, the focus will be on one asset, the vacuum compressor pump. The PdM programs applied to the vacuum compressor pump will focus on bearing failure using vibration analyses. Using some general information, it is possible to narrow down the program options, but there is still a wide variety that could be applied. This is because the effect of the sample frequency and the ability to detect bearing damage are related and are difficult to determine. So to be able to select a PdM program, the program's cost-effectiveness related to the sample frequency and detect-ability should be analysed.

In the literature, insight into the cost-effectiveness of maintenance aspects is gathered using a simulation model, but as already presented, these are developed to gain insight into strategies or policies. In this research, a simulation cost model will be proposed that will be used to gain insight into the cost-effectiveness of a selection of PdM programs. The simulation cost model results are expected to help Duyvis select the most cost-effective PdM program for the vacuum compressor pumps.

So, in short, the problem is the lack of information that can be used to determine the most cost-effective PdM program for the vacuum compressor pump at Duyvis. This lack of information is due to the unavailability of a simulation tool that could provide insight into the cost-effectiveness of PdM programs related to the aspects that are difficult to determine.

## 1.3. Scope

The problem statement made clear that the selection of a cost-effective PdM program is challenging. The following scope will be used to structure the research. The main boundary is the decision to develop the model specifically for one asset at Duyvis, the vacuum compressor pumps. These pumps are critical assets and have a discontinuous operating profile, making it difficult to directly determine the most cost-effective PdM program. Related to the asset and the application at Duyvis, the following boundaries are used throughout the research.

- The maturity level of the PdM programs are level 2, 3 or level 3 plus. The different maturity levels have been discussed in the research by Mulders and Haarman [23]. Level 3 plus is a new level that will be assessed and incorporated in this research. A combination of a level 2 program and a level 3 program is used in this level.
- The PdM program options have to be provided by a service partner of Duyvis. The options for the PdM program are either supplied by Turck or by SKF. The information on the PdM programs will be related to specific options provided by these distributors.
- The cost information is all related to Duyvis and their maintenance and service partners.
- Vibration monitoring is the condition monitoring technique used for the data acquisition for the different PdM programs. Used to assess the condition of the bearings used in the asset.
- The asset focused on is a vacuum compressor pump, the Busch MINK MM 1322 AV.
- A discrete event simulation technique will be used for the simulation cost model.

## 1.4. Research objectives

Now that the problem is clear, the following research objectives are set.

- An overview of different PdM programs that can be cost-effective for the vacuum compressor pumps at Duyvis.
- A simulation cost model that can assess the cost-effectiveness of different PdM programs for the vacuum compressor pumps.
- An advice on the most cost-effective PdM program for the vacuum compressor pumps at Duyvis.

## 1.5. Research questions

Combining the problem statement and the research objectives have led to the following main research question. During this thesis, an answer will be provided on this question by answering sub-questions and developing a simulation cost model.
The main research question is,

***How can predictive maintenance be applied in the most cost-effective way to the vacuum compressor pumps at Duyvis?***

The sub-questions that will be used to structure the research and provide information to be able to answer the main research question are as follows:

1. *How is predictive maintenance applied in practice?*
2. *What are the focus points for the application and analysis of predictive maintenance programs at Duyvis?*
3. *Which predictive maintenance programs will be analysed on their cost-effectiveness related to their application on the vacuum compressor pumps?*
4. *How is the cost-effectiveness of the predictive maintenance programs analysed?*
5. *How can the simulation cost model give insight into the cost-effectiveness of the predictive maintenance programs?*

## 1.6. Contribution

With this research, the following two scientific contributions will be made. The first is focused on developing a simulation model, while the other focuses on adding and assessing a new maturity level for PdM programs.

**Simulation cost model.**
This contribution has already been globally introduced. Currently, the literature focuses on maintenance strategy and policy selection problems. There are tools developed that can assist the maintenance department in selecting the most cost-effective maintenance strategy or policy. This is for instance done in the following papers, [3, 7, 11, 45].

Currently, there are tools and information available that can be used to select the most cost-effective maintenance strategy and policy, but there is a lack of information or support tools that can be used to select the program that will be used to implement the policy and strategy. This gap in the literature will partially be closed in this research. A simulation cost model will be developed. The simulation cost model will be built to analyse the cost-effectiveness of PdM programs that can be applied to the vacuum compressor pumps at Duyvis.

The simulation cost model will work with a discrete event simulation in combination with a cost model. The model will use the difference in the detect-ability and sample frequency of the different PdM programs. More information on the built-up of the model will be presented in section 5.2. The results of the simulation will give insight into the reliability of the asset and the overall cost. This information is used to advise on the most cost-effective PdM program for the vacuum pups at Duyvis.

**Level 3 plus**
Besides the development of a simulation cost model, a new maturity level will be added and assessed. As already mentioned, PdM programs can be applied according to four different maturity levels.
This research will not stick to the strict boundaries of the four levels but will add a level that combines the aspects of two levels to create a new level. As presented by Mckone and Weiss [21] it is important to consider combinations and not directly abandon valuable aspects when there is a possibility for a more promising new technology. In the paper, this is related to the combination of maintenance policies. In this research, the philosophy is applied to the maturity levels of PdM programs.

The extra level that will be added will be called level 3 plus. Level 3 plus combines an online real-time monitoring application with instrumental inspections related respectively to level 3 and level 2. The new level is expected to give the ability to combine the best aspects of both applications at a lower cost. In this research, a level 3 plus option will be proposed and analysed on its cost-effectiveness related to the vacuum compressor pumps at Duyvis.

## 1.7. Outline

The information provided throughout the research will form the basis for answering the main research question. The following outline is used in the research.

The research starts by gaining more knowledge on the application of PdM in practice by performing a literature study, chapter 2. The literature study will first focus on three main maintenance policies. The application of a PdM program will be discussed next. The final aspect is to zoom into the current application in practice related to the different maturity levels.

Using the general information, it is time to zoom in on the case study. By defining the focus point for the PdM program at Duyvis. First, the current situation is assessed. Followed by selecting the critical asset. In the case study, this is the vacuum compressor pumps. The failure behaviour and the operating profile of the pump will be presented. The failure behaviour will lead to the focus point of bearing failure. Which will be the central aspect analysed to determine the condition of the asset. Due to this, more information on bearing failure will be provided. The last step is to select the focus point for analysing the PdM programs. The cost-effectiveness of PdM programs will be analysed by focusing on two KPIs.

In chapter 4, a selection will be made on PdM programs that can be used at Duyvis and should be analysed. First, some decisions are made regarding the three steps of a PdM program. The first aspect will be focused on collecting the data. The condition monitoring technique will be selected and discussed. Followed by decisions regarding the application of the sensing device. The next step is data analysis, some techniques will briefly be explained. The final step is related to decision making. Here the different types of maintenance planning options will be presented. The information on the different aspects of the PdM program will be used to narrow down the PdM program options. An overview will be given of the programs that will be analysed on their cost-effectiveness.

Chapter 5 will be used to introduce the simulation cost model. The simulation cost model will be used to assess the cost-effectiveness. First, the simulation technique will be selected, followed by information on the built-up of the model. The model consists of a simulation model and a cost model. Also, information on the input, output and assumptions of the model will be presented. The model will be adjusted to simulate the different programs. How this is done is discussed in the final section of chapter 5.

Using this information, it is time for the implementation and the result, chapter 6. The implementation focuses on the verification of the model and sensitivity analysis. After these steps, the model can be used to analyse the cost-effectiveness of the different programs. 4 tests will be performed, focusing on the aspects that could influence the KPIs. The results of the tests will be discussed, and the information in the chapter will give insight into the limitations.
Using all the information provided in the research, the final step is to answer the main research question and propose further research.

# 2
# Predictive maintenance in practice

Some general information about the application of PdM in practice is presented to have a clear overview before analysing the cost-effectiveness of a PdM program. The information is gathered by conducting a literature study. First, the three main maintenance policies used in practice are introduced. Followed by an introduction to the components that built up PdM programs. The final section will focus on the maturity levels of a PdM program.

## 2.1. Maintenance policies

Maintenance activities are the actions that are taken with the intention to retain or restore an item or system to a state where it is able to perform its function [3]. These actions are structured using a maintenance strategy. A maintenance strategy is built up of a combination of maintenance policies. In general, there are three main maintenance policies used to form maintenance strategies. These three maintenance policies form the basis for various varieties.

The three main policies are corrective, preventive and predictive. Corrective and preventive maintenance are widely used, but the application of PdM has increased rapidly with the increase in big data possibilities. The three policies have been described in many papers and do overlap in some areas. The definition provided in this research is the most common classification of the policies and is widely used in the industry [32]

**Corrective maintenance**
Corrective maintenance is the oldest maintenance policy there is [46]. It is also referred to as reactive maintenance, run-to-failure maintenance, failure based maintenance, fire-fighting maintenance or breakdown maintenance policy [4, 18, 32]. As can be seen from the different names. Corrective maintenance is a policy that waits for failures to occur before actions are taken. This maintenance policy is the simplest and cheapest policy to implement. There is no use of detection or prevention techniques [32]. The initial cost may be low, but the maintenance cost could become high. The result of the cost related to the loss of production capacity and higher cost for labour and parts [32, 47]. However, in some cases, if the consequences of the asset failing is insignificant, this policy is still cost-effective [14, 32]. For instance, when the asset is not critical, and an unexpected breakdown will not affect the overall production capacity. Or if maintenance actions are quick fixes.

**Preventive maintenance**
The second maintenance policy is preventive maintenance. This maintenance policy, as the name already says, is focused on preventing failures from happening. In this policy the maintenance activities are planned. The planning can be based on multiple aspects such as time, age, calendar, or usage. Most commonly, time-based preventive maintenance is used. In this case, the planning is done according to the reliability characteristics of the equipment. The characteristic of the asset gives information on the expected time between failures. This indication will be used to determine the best periodic time for maintenance activities. This maintenance policy reduces the number of unexpected failures. How-

ever, the downside of this maintenance policy is that parts tend to get replaced before the end of their lifetime [18, 45].

**Predictive maintenance (PdM)**
So to solve the problem of performing maintenance actions too early but still keeping the number of unexpected breakdowns as low as possible, a new maintenance policy has emerged, predictive maintenance (PdM). PdM uses information on the current condition of the machine to be able to plan maintenance activities. The data gathered with this policy is assessed to find signs of deterioration. Using this information makes it possible to plan maintenance activities only when there are signs of deterioration, reducing the number of unexpected failures and the cost related to premature replacement of parts. Also, it will give the opportunity only to change the parts that give signs of damage [18].

**Comparison**
The three maintenance policies discussed are very different and come with their advantages and disadvantages, provided in table 2.1 based on [18]. In this table, it can be seen that there is a significant difference in the advantages and disadvantages of the different policies. Nevertheless, they are all related to cost. Cost related to failure, inventory, mechanics or equipment.

For example, the cost for inventory is higher with corrective maintenance than with preventive maintenance. Because corrective maintenance requires more spare parts in inventory, there is no knowledge of the time and type of maintenance required. With preventive maintenance, the maintenance activities are planned. So the spare part in inventory can be low, the parts can be ordered to be just in time for the maintenance actions. With PdM, the cost related to inventory can be even lower due to the prior knowledge of the specific part that is damaged.

An advantage of corrective maintenance over the other two policies is the costs required for implementing the policy. For corrective maintenance, this is null. There is no need for equipment or training to be able to implement this policy. The cost related to the implementation of the policy increases for preventive and is even higher for PdM. There is some cost related to determining the best interval for preventive maintenance, but this is very low compared with PdM's upfront cost. PdM requires equipment and training when to be implemented.

| **Corrective** | **Preventive** | **Predictive** |
|---|---|---|
| **Disadvantage** | **Disadvantage** | **Disadvantage** |
| High risk of catastrophic failures, resulting in high maintenance costs | Risk or replacing parts too early, resulting in high replacement costs | High investment cost due to the equipment needed for condition monitoring |
| | | **Advantages** |
| High risk of unplanned downtime | Moderate risk of unplanned downtime | Low risk of unplanned downtime. |
| Inventory cost are high for spare parts | Part tend to get replaced too early, not sustainable | equipment life is extended |
| | **Advantages** | |
| High labour cost, due to unplanned maintenance | Helps to prevent unplanned breakdowns | Maintenance can be carried out when most convenient |
| **Advantages** | | |
| No investment costs | Fewer catastrophic failures | High control over inventory |
| An easy option | Maintenance can be carried out when convenient | Opportunity to only replace parts that are damaged |
| | Control over inventory | Opportunity to understand why equipment is failing |

Table 2.1: Disadvantages and Advantages of maintenance policies. *Based on [18]*

Due to the different advantages and disadvantages, it is wise to make a well-informed decision regarding the most appropriate policy for a specific situation. The first step will be to determine the criticality of the asset. The asset's criticality will indicate if the use of condition monitoring, thus a PdM policy, is required and to what extent. This last part, to what extend, refers to the different ways PdM can be applied. PdM is applied according to a PdM program.

## 2.2. PdM Program

Predictive maintenance is the focus of this research. PdM is applied using a PdM program. Selecting a PdM program is the third step of the application process of a PdM policy. The steps taken to apply a PdM policy are:

1. Determine current situation and wishes for the future
2. Selecting machine/asset according to criticality
3. Selecting the PdM program. more on this below.
4. Setting safe operating parameters and the baseline of the asset
5. Determine the condition of the machine using the PdM program selected
6. Maintenance activities if required

These steps are based on [30, 34, 35]. The first three steps will be incorporated in this thesis, with special attention to step 3: selecting the PdM program. Before providing information on the steps related to the case study, first, some general information about a PdM program.
A PdM program, also referred to as a condition monitoring program, consists of three main parts: 1) data acquisition, 2) data processing and 3) decision making [16, 32]. These three parts are required to determine the condition of the asset. The first step is data acquisition which is gathering the data. The data is analysed in step 2, and the analysed data will be used to advise on the type of maintenance planning required related to the asset's condition, step 3. More information on how the different parts of a PdM program work is presented below.

**Data acquisition**
The first step of a PdM program is data acquisition. Data acquisition refers to collecting analogue data from a sensor and converting it to a digital signal that the computer can process. A sensing device is used to collect the data, and a DAQ device is used to process it. This first step is critical for applying a PdM policy. The data gathered in this step will be used throughout the PdM program to determine the machine's condition.
The data collected can be categorised into two categories: event data and condition data. Event data is related to the maintenance activities, so what is done, when it is done, and the causes of the damage. The second part is data that will be used to provide information on the condition of the asset.
The condition data can come in various forms and is collected using a condition monitoring technique. There are multiple options for condition monitoring techniques. The technique used depends on the type of asset being analysed, its failure behaviour and the information required to determine the condition. A condition monitoring technique works with sensors, data communication systems and storage. All these aspects come in various options.

**Data processing**
When the data is gathered, the next step is to process it, step 2 of the PdM program. The data processing step consists of two parts, first cleaning the data and, secondly analysing the data.
The first step, cleaning the data, is essential in data processing. Not just for PdM programs but always when data is used. Cleaning the data will reduce the chance of a "garbage in, garbage out" situation [16]. There are multiple ways of cleaning the data. However, this is not inside the scope of this research. For selecting a cost-effective PdM program, it will be assumed that the data is cleaned effectively in all the programs that are being analysed.
The second step is data processing. There are multiple models, algorithms and tools available in the literature that can be used to analyse data. The data is analysed to gain a better understanding and make a more detailed interpretation of the information. In the paper by Jardine et al. [16], different analysing techniques are presented. In general, the type of model, algorithm or tool used to analyse

the data is related to the data type [16]. The data gathered in the first step, the data acquisition, can be in various forms. The three main categories are:

1. **Value type:** single value data collected at a certain time used for condition monitoring. Examples: oil analysis, temperature, pressure and humidity.
2. **Waveform type:** A time series collected at a certain time used for condition monitoring. Examples: Vibration analysis data and acoustic data.
3. **Multidimension type**: Multidimensional data collected at a certain time for condition monitoring. Example: image data such as infrared thermographs, X-ray images and visual images.

The condition monitoring technique used in the data acquisition step highly influences the type of data available, influencing the techniques available to analyse the data. For now, this will be all the information provided on this step. More specific information related to the case studies PdM program, and its possible analysing techniques will be presented later.

**Decision making**

The final step of a PdM program is decision making. This final step uses the analysed data to indicate the condition of the asset. This indication will be used to decide on the maintenance actions [16]. How the maintenance actions are planned depends on the asset's current condition and the indication of the expected failure time. Detecting the damage is referred to as the diagnosis of a PdM program. While predicting when a failure will occur is related to the prognosis [16]. Prognosis is the more advanced tool of the two. However, the techniques used for prognosis require a lot of data and information. Also, a diagnosis will always be required.

## 2.3. Maturity level

As already presented, PdM programs come in various application options. In general, the programs can be classified according to 4 maturity levels, presented in the research by Mainovation and PWC [23]. The different levels differ in the amount of big data and statistics used. Which relates to the reliability of the strategy. Figure 2.1 contains an overview of the 4 levels related to their big data usages and reliability.

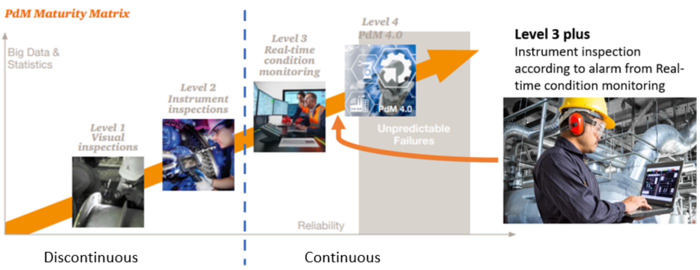



Figure 2.1: Maturity level PdM programs, *based on[23]*

The levels presented in the figure are described as follows [23]:

- **Level 1 Visual inspections:** Physical periodic inspections done on a periodical basis. The conclusions are only based on the expertise of the inspector.
- **Level 2 Instrument Inspection:** The periodic inspections are now done with the use of an instrument. The conclusion is based on a combination of the inspector's expertise and the data gathered with the instrument.
- **Level 3 Real-time condition monitoring:** (semi)continuous real-time monitoring of assets. The conclusions are now solely based on data. The alerts are based on pre-established alarm levels.
- **Level 4 PdM 4.0:** (semi) continuous real-time monitoring of assets. The conclusions are solely based on data. However, the alarms are now based on predictive techniques, such as regression analysis.

The main difference between the 4 levels is that levels 1 and 2 are discontinuous processes, and levels 3 and 4 are continuous. Directly related to the way the data is collected. With a level 1 or 2 program, the data is collected through performing inspections. While levels 3 and 4 use an online monitoring system to collect the data. The online monitoring system increases the sample frequency exponentially.

Another interesting aspect related to the different PdM maturity levels is the way conclusions are made. With a level 1 strategy, the ”data” is the sound, smell, touch and look of the asset collected by the mechanic using his senses. The problem is that it is very subjective and difficult to quantify. A level 2 strategy is more advanced than level 1. The mechanic still has to perform inspections but will now use an portable instrument to gather the data. Using an instrument to collect the data makes it possible to detect damages more accurately. Also, the data is can now easily be interpreted by other people. The data collected using the instrument is suited to be analysed using more advanced analysing techniques.

With continuous applications, the data is collected using an online sensor application. The difference between a level 3 and 4 strategy is what is done with the gathered data. With a level 3 strategy, the maintenance activities are planned based on pre-set alarm levels. On the other hand, the data collected with a level 4 strategy will be analysed with more advanced techniques, such as machine learning algorithms. The alarm generated by a level 4 strategy will generally be more reliable but requires higher quality data and more expertise to interpret.

The different maturity levels can be related to the three steps of the PdM program. All the steps are performed for each level, but the way they are applied changes. The data acquisition is either done through online sensors or with inspections with or without using an instrument. The different ways of collecting the data result in different options for data processing. Some tools, methods or techniques require a minimum quality of data. The levels also indicate how the decisions are made. In level 1, the decision is entirely based on the finding of the mechanic, while in a level 4 approach, the data processing is entirely done by a computer, directly resulting in maintenance action advice.

### 2.3.1. Level 3 plus

Besides the levels already presented in [23], a new level will be added, level 3 plus. This level combines a level 2 program with a level 3 program. Level 3 plus is also presented in figure 2.1.

As stated by Mckone and Weiss [21], it is important to not simply abandon valuable maintenance policies for the promise of new technology. In Mckone and Weiss [21] it refers to combining preventive maintenance with predictive maintenance. Nevertheless, the same could be said when improving a PdM approach. It is wise to keep in mind that combining two different programs could result in an even better program. This research will include a level 3 plus approach to see if the expectations are correct and if a level 3 plus approach could be a good contestant when selecting a PdM program. It is expected that the online monitoring application can be less advanced related to the quality of data. Because the data collected with the inspections can have a higher quality, which could lead to good cost-effectiveness.

Another aspect that should be mentioned when a level 2 and a level 3 program are combined is the ability to make decisions. Using inspections will increase the amount of event data available. Inspections require the mechanic to go to the asset, which allows assessing other problems directly. Problems that the online monitoring application might not detect. An online monitoring application can analyse the aspects that have been determined beforehand. However, it could be the case that something unexpected, such as a blocked filter or oil leakage, is occurring. Detecting this in time might make it possible to prevent a failure or damage from happening. This aspect related to the PdM program and level 3 plus is outside the scope of the simulation cost model but should be kept in mind when the results are close between a level 3 plus and a level 3 approach.

### 2.3.2. Current PdM level adoption

In the research conducted by PwC and Mainovation, not only the different maturity levels are introduced. Also, research has been done on the current PdM level adoption. In the research, 280 companies from Belgium, Germany, and the Netherlands have been surveyed [23]. They were asked multiple questions

about their PdM approach. From the 280 companies, 175 perform maintenance activities for production locations, either in-house or as an external partner.
This research made it clear that most companies have a PdM program in place (97%). Currently, 27% are at a level 1, 36% at level 2, 22% at level 3, and only 11% is already at a level 4. The percentage of companies that use a level 4 approach is expected to increase rapidly over the coming 5 years [23]. Nevertheless, to get there, some hurdles will have to be taken.

The different levels have different requirements, and much historical data is required for a level 4 program. The availability of data is seen as the highest critical success factor. 60% of the companies see the availability of data as the biggest problem in implementing a level 4 program. The amount of data can be increased by gathering data accurately and completely as soon as possible.
Collecting data can be done by implementing a level 2 or level 3 PdM program. If a level 2 or 3 program is in place, planning a level 4 program application can start. The data will provide insight into how and where a level 4 PdM program could best be applied [23].

Due to the urgent need for data, it is advised to start with a level 2 or 3 program as soon as possible. However, it is still key to make a well-informed decision on which program would be best suited for the asset in question. The decision is to focus on a level 2, 3 or 3 plus application related to the information.

## 2.4. Conclusion

The literature study conducted gave insight into the current application of PdM programs in practice. This information is used to answer the first sub-question. In general, it can be concluded that PdM is applied in practice with a level 2 PdM program. However, there is a trend towards level 3 and 4 programs. The specific application used for a PdM program in practice differs per situation due to the countless options available on the market.

# 3

# Program Focus Duyvis

Chapter 2 provided information on how PdM is applied in the industry. Now it is time to zoom into the case study, PdM programs for Duyvis. Like most companies in practice, Duyvis has a PdM program but would like to improve this to a more cost-effective program.

Selecting a PdM program is challenging due to the high number of options available on the market. Due to this, there is a danger of falling into a technology trap, meaning that the decision-maker will go for the most advanced option because they believe it is the best option available. However, this is not always the case. A decision for condition monitoring practices should be driven by financial, operational, and safety requirements and not by the available technology [34].

Selecting a PdM program should be a well-informed decision. The model proposed will be able to analyse the cost-effectiveness of PdM programs. However, first, a selection from the programs available should be made. The first step is to select the focus point for the application and analysing of the PdM program. In the paper by Shrieve [34] implementation steps are proposed for selecting the focus point for the most cost-effective condition monitoring program. Adjusting these steps for Duyvis results in the following implementation steps:

1. Identify the current PdM program
2. Identify the critical asset that is the focus of the program
3. Identify the assets failure behaviour
4. Identify which failures can be detected with a PdM program
5. Identify requirements for the PdM program
6. Identify the objective and KPI's

These steps will be discussed in this chapter. The result will be a focal point for applying the PdM programs and a focus point for analysing the programs.

## 3.1. Current situation

The first step is to identify the current situation. Currently, Duyvis is using a maintenance strategy consisting of corrective, preventive and predictive maintenance. The type of maintenance policy used depends on the criticality of the asset.

Since this research is focused on PdM and improving PdM programs, this aspect will be highlighted. The current PdM program used is a level 2 program. This PdM program is used on the rotating equipment at Duyvis. Duyvis has 195 rotating assets, such as pumps, motors, fans and mixers, maintained according to the PdM policy.
A level 2 PdM program means that instrumental inspections gather the data. An external service partner, Facta, performs the inspections. Facta is a specialist in rotating equipment. They maintain, overhaul, improve and deliver rotating equipment such as pumps, generators, and gearboxes [9].

The inspections by Facta are done every four months, so three times per year. The inspection interval used to be four times per year, so every three months. Due to the high inspection cost and a large amount of data that needs processing after each inspection, the frequency was reduced. However, reducing the frequency increases the chance of missing damage, resulting in a higher chance of an unexpected breakdown. In 2020 the cost where €21000 for 4 inspections. In 2021, when 3 inspections are performed, the cost related to the PdM program will be €15750.

In short, the following PdM program is used to collect and process the data and make decisions. The focus of the PdM program is on bearings. The bearings are analysed using vibration analysis as the condition monitoring technique. The data is collected using a Microlog, broad range, sensor. The Microlog is a handheld sensor application provided by SKF that can be placed on the housing of the asset to collect the data. A quick view of the data is directly visible, and the data is also uploaded to the cloud of Facta for further analysis [40]. The data is gathered in timewaveform. Analysing the data will provide insight into early signs of damage. The analysis of the data has to be done by experts at Facta. A rapport will be made available for Duyvis with colour codes per asset when the data is analysed. The colour represents the current condition of the machine. If the asset is not in optimal condition, a recommendation will be given on the maintenance activities planning.

## 3.2. Critical asset

The next step is to select the critical asset that will become the focal point of the PdM program. Criticality of an asset is within PepsiCo determined by assessing three aspects:

- Impact on the process.
- Influence on health and safety conditions.
- Time required for maintenance, related to the repair costs.

Looking into these aspects it will be possible to categorize the assets in one of the three criticality categories. Descriptions of these categories are presented in table 3.1 [18], moving from most critical to the least critical category.

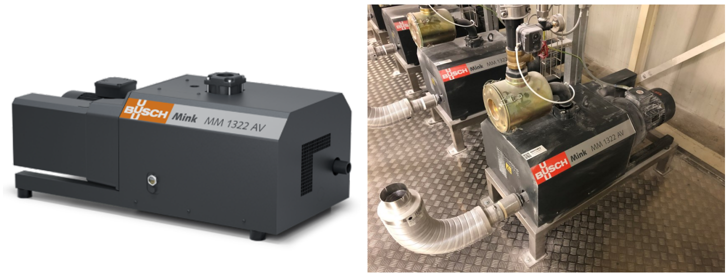
| **Category A** | **Category B** | **Category C** |
|---|---|---|
| Large impact plant output<br>Significant repair costs<br>Can cause significant health and safety impacts when failure occurs | Lesser impact plant output<br>Moderate repair costs<br>Might have health and safety impacts when failure occurs | Little/No impact plant output<br>Small or limited repair costs.<br>no health and safety impacts when failure occurs |

Table 3.1: Descriptions of criticality categorizations. [18]

Assessing the criticality of an asset will provide information on the type of maintenance policy that should be used and to what extend. In general, only high critical assets require condition monitoring. If an asset has short repair times and damage results in no or minor limits to the production capacity, a corrective or preventive policy would be sufficient [18].

At Duyvis, there are multiple critical assets. Either due to their impact on the production process, their remote locations, high maintenance cost, or their impact on health and safety conditions. For this research, the decision is made to focus on the vacuum compressor pumps. These are critical machines of category A. Due to their effect on the production process and the high cost of maintenance related to these machines. If a vacuum compressor pump fails, this will reduce the production capacity by 60%. Also, the time required to perform and plan maintenance actions is relatively high due to the lack of spare parts.

There are 4 vacuum compressor pumps placed next to each other at the production plant. They are used for the transport of flour from storing silos to mixers. The flour is used to coat the peanuts, either a pre-coat or regular coat, depending on the type of product produced. The vacuum pumps used are the BUSH Mink MM 1322 AV dry claw pumps, presented in figure 3.1. In the following section, the working principle will be presented, followed by the operating profile of the pumps. More information on the asset is presented in appendix B.1.




(a) Product catalogue picture [6]    (b) Pump at Duyvis

Figure 3.1: Mink MM 1322 AV vacuum compressor pumps

### 3.2.1. Working principle

The vacuum compressor pumps used at Duyvis are dry claw vacuum pumps. They use a claw principle. In figure 3.2 a schematic representation of the rotating claw working principle is presented.
Two counter-rotating, synchronized, non-contacting claws (3) are placed inside the pumping chamber (2). The claws are placed with utmost precision to ensure no contact between the two rotating claws. However, the gap between the 2 rotating claws is small enough to maximize efficiency. A motor is used to power the claws. The air is filtered before it enters the pumping chamber through inlet (1). The claws rotate, and due to the change in available space, the air is compressed. The rotation of the claws results in lower pressure on the inlet side and higher pressure on the discharge side. The compressed air is discharged at the outlet (4) [28].

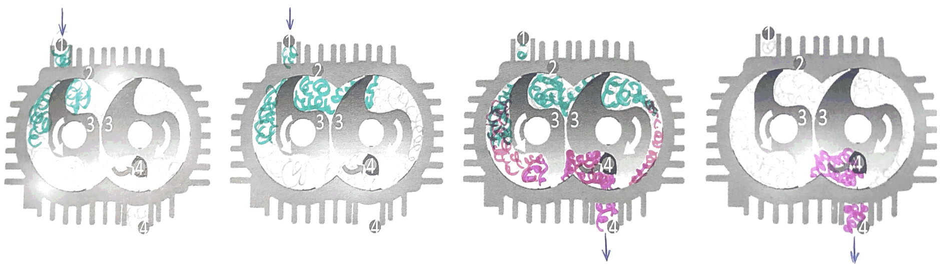
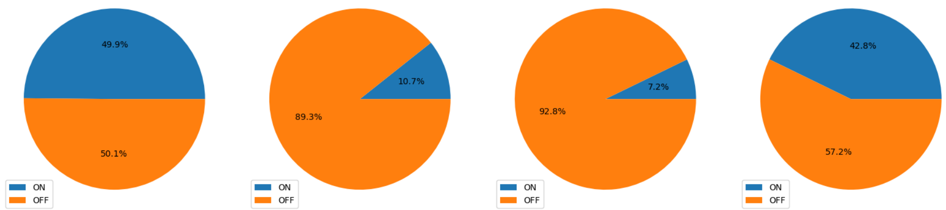


Figure 3.2: Schematic representation of working principle

### 3.2.2. Operating profile

The 4 vacuum pumps are placed next to each other to transport different types of flour from silos to the mixers. The vacuum pumps have a discontinuous operating profile. On average, the pumps are ON for 11 minutes per cycle, but the ratio between ON and OFF conditions differs per pump. The ON/OFF ratios of the pumps are determined by analysing the operating profile. The data on the operating profile is gathered using a PLC observer. The PLC observer has collected the condition of the asset, ON or OFF, for a week. This information is used to determine the different ON/OFF ratios of the pumps. The pumps are ON for 7% to 50 % of the time. In figure 3.3 the ON/OFF ratios of the different pumps are presented. More information on the working profile of the machine is presented in appendix B.2.
This discontinuous operating profile could influence the amount of useful data. It is essential to consider the ON/OFF ratios' effect when analysing the different programs. The PdM program selected will be applied to all 4 pumps and should be cost-effective for all situations.




(a) VCP 1 (b) VCP 2 (c) VCP 3 (d) VCP 4

Figure 3.3: ON OFF ratios of the pumps

## 3.3. Failure behaviour vacuum compressor pumps

The third step is to determine the failure behaviour of the asset, in this case, the vacuum compressor pump. The expertise of Rob Visser and Wout de Clerck from Atlas Copco and Martin Franssen from Busch has been used to get more insight into the vacuum pump's failure behaviour. They work for the technical support department of their representing companies. Notes on the meetings have been added to appendix C. In combination with information found in the literature, the expert information is used to determine how the pumps fail and the failure distribution.

### 3.3.1. Failure Cause

Every machine has weak spots. These weak sport can cause a failure to occur, related to a certain part of the asset or due to the operating profile and conditions. A vacuum compressor pump, in general, fails due to blockage or bearing failure, [R. Visser, Atlas Copco, personal communication, 25-5-2021]. These two reasons for failure result from different aspects, but both could result in catastrophic failure of the machine.

The first reason is a blockage. Blockage occurs when there is a build-up of dirt on the rotating claws or in the pumping chamber. The two rotating claws are placed next to each other with only a minimal gap. Air going through the machine might have some particles that can build up on the claws, closing the gap in between. To prevent this from happening a filter is used. However, this results in another area that is of blockage risk. Filters are very useful, but they require much maintenance to make sure they do not get clogged. If this is not done, a clogged filter will result in the loss of vacuum in the pumping chamber, resulting in a higher pressure inside the pump, which could tear the filter. If this happens, all the dirt from the filter gets pulled into the machine resulting in catastrophic failures. Figure 3.4 contains pictures of flour residue pulled into the machine.

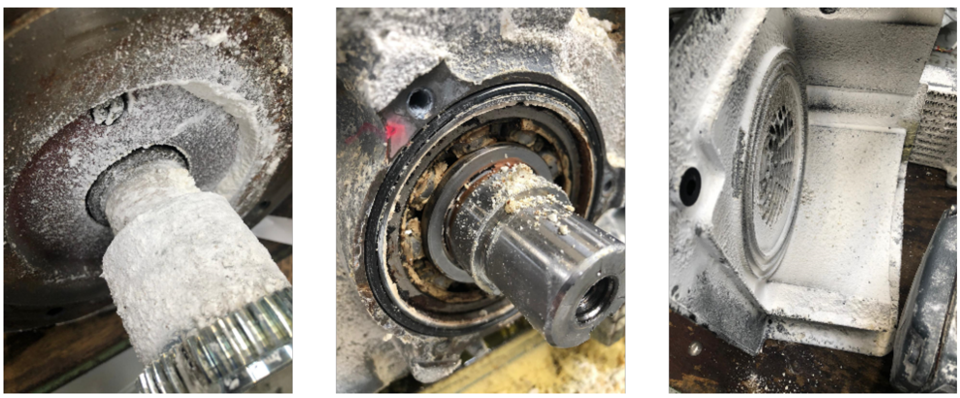


Figure 3.4: Result of blockage, Flour inside vacuum pump

The problem with this failure mode is that the PF curve is very steep. The PF curve is the predict - failure curve. This curve describes the relationship between the signal time, time of detection, and the actual time of a failure [21]. If the PF curve is steep, the time between the prediction of the failure and the actual failure is short. In the case of blockage, it is as short as minutes. Due to this, PdM is not suited to be applied for this failure mode. However, it is advised to implement a fail-safe on the machine. Working with pressure measurements. If the pressure inside the machine increases above typical values, the machine should directly stop to prevent tearing the filter.

The other failure reason is bearing damage or failure. Bearings are used in rotating equipment to support the load and maintain clearance between the stationary and rotating elements. Bearings form one of the most critical parts of rotating equipment. A mere 10% of rolling element bearings reach their expected life [12], making bearing failure a common cause of failure in rotating equipment.
The failure of bearings has a longer PF curve, making it very suitable as a basis for a PdM program. More information on bearing failure will be presented in section 3.4.

### 3.3.2. Failure distribution

As already discussed, the vacuum compressor pump can fail due to bearing failure or blockage. Using fail-safes and proper maintenance, the chances of blockage can be limited. Bearing failure will be analysed using a PdM program. To detect damages and plan maintenance activities accordingly. To be able to analyse the different programs, information on the failure distribution is required. The failure distribution presents the probability of a pump failing at a specific time, the probability of selecting a certain end-of-lifetime (EoL).

Information on this aspect has proven challenging to find due to the lack of factual information on this subject for the vacuum compressor pumps. It is indicated that the EoL of vacuum pumps is highly influenced by the operating conditions, such as temperature, speed, load, and humidity. Due to these aspects, it is complicated to determine precisely when a failure will occur for a specific situation. Due to the lack of factual information, the expertise of Wout de Clerck and Rob Visser from Atlas Copco and Martin Franssen from Busch has been used. Meetings have been conducted to gain insight into their experience on the failure behaviour of the vacuum compressor pumps. Notes on the meetings have been added to appendix C.

The information gathered indicates that the vacuum compressor pump has multiple aspects that can lead to failures. As indicated by Wout de Clerck, failures can be related to bad manufacturing or bad practice. Poor manufacturing will lead to early failures, which is referred to as infant mortality failures. Bad practice failures are related to the guarantee period of the asset. The asset has a guarantee period of 1 year. Generally, failures start to occur after this point but before the second year. If the failures are in general later the guarantee period would be longer. Besides these failures, it is also discussed that the asset could run for years without a failure, Wout de Clerck, Rob Visser and Martin Franssen all mention this. In this case, the asset will eventually fail due to old age, related to wear-out failures.
It is difficult to determine the exact failure curve due to the lack of information, but in this thesis, the use will be made of the information provided above and some assumptions.

## 3.4. Bearing Failure

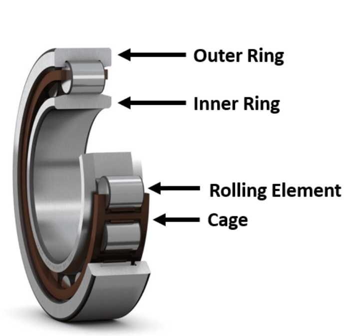
The fourth step is to identify which failures can be detected using a PdM program. From the two possible failure causes for the vacuum compressor pumps, only bearing failure is suited for a PdM program. Bearing failure is a common focal point of a PdM program, and an extended amount of information is available on this subject. Also, the market has multiple options available for various PdM programs related to this failure cause. Nevertheless, first, some more information on bearings, failure causes and failure stages.

### 3.4.1. Bearing design

Bearings come in a variety of forms and sizes. However, they can be classified into two categories, Rotary motion bearings and linear motion bearings. More than 90 % of rotating machinery elements have a rotary motion bearing [12]. The rotary motion bearing can either be a ball bearing or a roller bearing. The only difference between the two is the use of balls or rollers inside the bearing. A bearing consists of an outer ring, the rolling elements, balls or rollers, sometimes a cage, and an inner ring [24].

Between the roller elements, lubrication is used for smooth movements.

The vacuum compressor pump used at Duyvis has 4 bearings inside the pump. Two of them are SKF NU 208 ECP: Cylindrical roller bearings, single row. The other two are SKF 3309 A: Angular contact ball bearings, double row [M. Franssen, Busch, personal communication, 19-10-201]. Respectively presented in figure 3.5a and 3.5b. The bearings are used inside the pump to rotate the claws. In Appendix B.1 the location of the bearings inside the pump is presented.




(a) Bearing 1: SKF NU 208 ECP [37]

(b) Bearing type 2: SKF 3309 A [36]

Figure 3.5: Bearing information

Besides the bearings inside the pump, there are also bearings inside the motor that powers the pump. The motor used is the IEC112 which is a standard industrial pump. This research will focus on the bearings inside the pumps. Through a meeting with Martin Franssen from Busch, it became clear that the bearings inside the pump fail in most cases. The load on the bearings inside the pump will be much higher than on the motor bearings. Notes of this meeting are added to appendix C.

### 3.4.2. Causes bearing failure

In general, it could be said that bearing failure is caused by bearing damage. However, this statement's problem is that bearing damage is very rarely the source of the problem[38].
Multiple aspects can cause a bearing to get damaged and fail. According to SKF, in general, $1/3$ of the failures occur due to fatigue. Similar, $1/3$ fail due to lubrication problems. These can be the wrong lubrication type, amount or interval. $1/6$ of the failures are due to contamination of the bearing, the result of ineffective seals. The remaining $1/6$ of the failures result from any other reason, such as improper design. [39]

The first aspect, fatigue, can be caused by several aspects. Either old age or due to mechanical problem. Mechanical problems are 1) Misalignment, 2)Imbalance, 3)Looseness and 4)Bent shaft. These four different mechanical problems are caused due to different aspects, but they all have the same effect. They cause a higher load on the bearing resulting in fatigue [38]. These problems will shortly be described here, more detailed information can be found in [38]

Misalignment occurs when shafts, couplings and bearings are not properly aligned along their centre-line. There are two forms of misalignment, angular or parallel. It is accepted that over half of all machine problems are caused by this aspect.
The second most crucial machinery problem is imbalance, covering almost the other half of all the machinery problems. Imbalance occurs when the shaft centre-line does not coincide with the geometric centre-line. There are three different types of imbalance, static, couple and dynamic which is a combination of the first two.
The third aspect is Looseness, the result of an improper fit between two parts. The final aspect is shaft bent, as the name already predicts, related to the bending of the shaft inside the bearings.

Bearing damage can be caused by different aspects, either mechanical problems or production faults.

The different causes of damage can cause different damage patterns in the bearings. If the damage results from a faulty production, the damage will be visible as roughness or waviness on the surface. If not the production process is the cause, but any other aspect the defect will be visible as indentations, scratches, pits, debris and particles. Experts can use these different forms of damage to determine the cause of the failure. Besides the different signs of failure, also the location of the damage can be different. Bearing damage can occur on all the different parts of the bearings, the balls, inner ring, outer ring or cage. The different causes and types of failure, especially the damage location, can be used in a PdM program.

### 3.4.3. Bearing damage stages

As already discussed, bearings can fail due to several reasons. However, the damage tends to evolve over 4 different damage stages, increasing in severity [12, 17, 26, 27]. Although this may not indicate the source of the problem, it can indicate the machine's condition. In figure 3.6 the different failure stages are schematically presented. The information presented below is related to typical spall or crack defects that can occur on bearings.

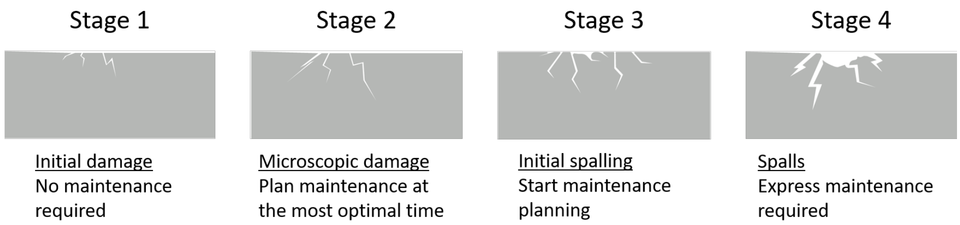



Figure 3.6: Bearing failure stages

- **Stage 1**: Damages start occurring. It is still below the surface and not visible. No direct actions have to be taken at this point. However, it is wise to keep monitoring the damages.
- **Stage 2**: The fault progresses, microscopic damages occur. The advice with a level 2 damage is to plan the maintenance actions for the most optimal time.
- **Stage 3**: The damage becomes more severe. The damages are now resulting in initial flaking, cracking and/or spalling. It is advised to start planning the maintenance actions immediately.
- **Stage 4**: The final stage of bearing failure. Multiple cracks, excessive flaking, or spalling is occurring. The bearing should be replaced immediately. Express maintenance actions are required.

The different stages of bearing damage from an important aspect of the simulation cost model due to the time left indication related to the stages. The effect this has on the advice on the required maintenance planning type will also be used.

## 3.5. Requirement

PdM programs focused on bearing failure come in a wide variety of application options. Due to this, it is essential to set some requirements to narrow down the options. The requirements are related to the asset being assessed, the type of failure and the company, Duyvis. In this section, the main requirements used to narrow down the options are presented.

The goal of Duyvis is to enhance their PdM program, either by changing the application or increasing the maturity. Currently, Duyvis has a level 2 program in place. So, they either want to enhance their level 2 program or implement a level 3, level 3 plus or level 4 program.
However, there is not yet enough historical data available to directly implement a level 4 program. So the PdM program should have a level 2, 3 or 3 plus maturity level, the first requirement. The program will gather data to eventually be able to implement a level 4 program.

The second requirement is related to the inclusion of Duyvis in the PdM program. The current program is completely executed by Facta, resulting in a situation where the knowledge is moved outside the organisation rather than inside. Duyvis wants to be more included in the strategy to enhance their understanding of the situation and assets. Resulting in the second requirement, the program has to have the possibility to be executed in-house. If an abnormality is detected, Facta will still be used for their expertise. But in general, the execution will be done in-house.

Requirement three is based on cost. The investment cost of a PdM program has to be below €2000 per asset. This requirement is related to the budget for the predictive maintenance policy.

Besides these three decision requirements, there are also functional requirements focused on the exact application of the program. Functional requirements include, among others, Mounting options must be available for the housing of the assets in question, there must be a 4G option, and the IP code of the product should allow application in the plant.

In this research, the focus will be on the decision requirements. The options provided have been assessed to ensure they follow the functional requirements.

## 3.6. Objective and KPIs

Besides forming a focal point for the application of the PdM programs, it is also essential to set a focus point for analysing the programs. This thesis focuses on selecting the most cost-effective PdM program for the vacuum compressor pumps. In general, cost-effectiveness refers to good practice with low cost. The meaning of good practice depends on the situation. This research focuses on two key performance indicators (KPI) overall cost and reliability.

The first KPI is the overall cost. The overall cost related to a maintenance program is very broad. In this research, the focus will be on three categories. The first category is the cost related to the maintenance actions. A change in the PdM program can influence the detect-ability of the different stages of damage. Which will influence the way the maintenance actions are planned, resulting in a difference in cost.
The second category is the cost related to unplanned downtime. Unplanned downtime is the result of an unexpected failure or late detection of failures.
The final cost category taken into account is the cost related to the PdM program. It is essential to consider multiple aspects related to the PdM program. The cost is a combination of the investment of the hardware and software (CAPEX) and the cost for the ongoing operation (OPEX) [34].

The second KPI will be reliability. The reliability of a program is in this study related to the number of unexpected breakdowns. Unexpected breakdown results in unplanned downtime. The number of unexpected breakdowns should be as low as possible to have a reliable program. Two other reliability aspects will be used when the number of unexpected breakdowns is the same for multiple programs. These aspects are the way the maintenance planning is conducted and the time available to plan. Time to plan is the time between detection and the expected failure. In an ideal situation, the number of unexpected breakdowns is zero and the time to plan the maintenance actions is long. However, the cost related to the program should be kept in mind, KPI 1.

It should be noticed that the reliability will partially influence the overall cost. The reliability influences the overall maintenance cost and the cost related to the downtime per program.

## 3.7. Conclusion

This chapter provided information on the application and analysis focus for the PdM programs assessed in this thesis, related to sub-question 2. The focus point for the application program is specific for the vacuum compressor pump and focuses on the failure behaviour. In this thesis, the focus is on the different stages of bearing failure. The focus point for the analysis of PdM programs is the cost-effectiveness related to two KPIs. 1) The overall cost based on maintenance, unplanned downtime and PdM program costs. 2) reliability related to the occurrence of unexpected breakdowns and the time to plan maintenance actions.

# 4 Program selection

The focus point for the PdM program has been made clear in the previous chapter. Using this information, decisions can be made regarding the different aspects of a PdM program. As already discussed, a PdM program consists of three main parts: 1) data acquisition, 2) data processing, and 3) decision making.

In this chapter, information is presented on aspects related to these main parts. First, information is provided on how the data is gathered, related to the data acquisition technique and the sensing device. The next step is to analyse the data. The techniques used for this process are discussed in section 2. The final step of a PdM program is decision making. In section 3, the result of the decision making is discussed. Finally, a selection of PdM programs that will be assessed on their cost-effectiveness is presented.

## 4.1. Data collection

The first step of a PdM program is data acquisition, collecting data [16]. To collect the data, first, a decision has to be made on the condition monitoring technique used. The condition monitoring technique gives insight into the type of information that is gathered. The next step is to decide on the hardware, what type of sensor is used. The selections made in this section will form the basis of the PdM programs.

### 4.1.1. Condition monitoring technique

Data used in the PdM program is collected using a condition monitoring technique. There are multiple options for the condition monitoring technique. The PdM program for the case study focuses on bearing failure. Narrowing down the condition monitoring techniques options to 4 possibilities.

**Ultrasound**

The first monitoring technique is ultrasound. Ultrasound technique is the newest condition monitoring technique for bearing failure and uses ultrasonic receivers, which are microphones that can be placed on the surface of the equipment close to the bearing.

Ultrasounds are created when there is friction. A bearing in good condition, especially well-lubricated bearings, will produce a smooth-rolling ultrasound. If these smooth-rolling ultrasounds change, this can indicate under-lubrication, over-lubrication or early signs of wear. If there is over-lubrication, the ultrasound will be very small, while under-lubrication increase the sound dramatically. If there are large spikes in the signal, heard as pops or crackles, this can indicate flat spots or scratches related to early signs of bearing damage or wear [25].

**Vibration analysis**
All machines produce vibrations when they are running, and this is the basis for vibration analysis. A sensor, in most cases an accelerometer, is placed on the housing close to the bearing to be able to detect vibration produced by the bearing [42]. In general, the vibration levels and frequencies measured are analysed to determine the condition of the machine [41].

Vibration analysis is the most commonly used vibration analysis technique for bearings[27]. This technique can provide information on imbalance, bearing failure, mechanical looseness, resonance, or bent shafts.

**Oil analysis**
The third condition monitoring technique is oil analysis. A common analysing technique and can be used for various purposes. When it is used for bearing failure, the oil is analysed on particles. The presence of particles in oil can indicate wear. The damage has to be at a severe stage to be able to detect particles in the oil [8].

**Infrared analysis**
Infrared analysis is a technique that is related to temperature. A thermal picture is used to detect if the bearing is generating more heat [41]. When the bearing is producing more heat, this can indicate more friction. This friction is related to the failure of the bearing. Also, the temperature of the machine, in general, can be monitored. If the machine increases in temperature, so will the bearing. If the bearing temperature increases, the lubrication of the bearing will become thinner, resulting in higher friction inside the bearing, which can lead to damage of the bearing [W. de Clerck, Atlas Copco, personal communication, 21-7-2021].

**Technique selection**
All the condition monitoring techniques mentioned above can be used to detect bearing damage. They use different techniques and focus on different parameters, either sound, vibration, particles or heat.
The different techniques can detect damage at different stages. In figure 4.1 a PF curve representing bearing failure is presented. P1, P2, P3, P4, indicate when the techniques are able to detect damage.

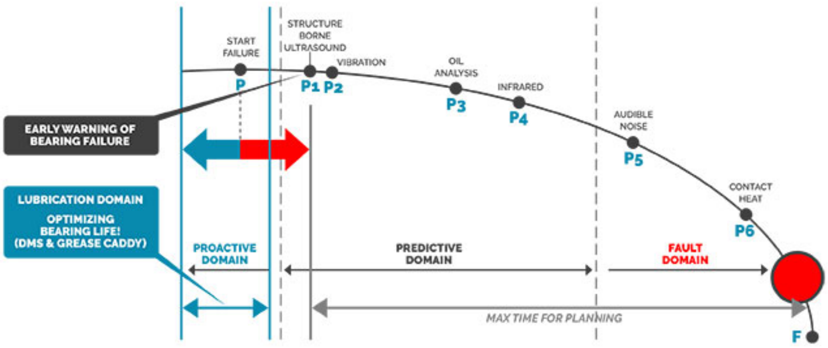



Figure 4.1: detect ability stages of condition monitoring techniques [43]

The Ultrasound technique can detect the earliest stages of damage, while the infrared analysis can only detect bearing damage in a severe stage. There is a smaller amount of time between the detection and the failure with infrared analysis than with the other options. Resulting in a limited time window to plan maintenance activities.

Related to the detect-ability why do companies not all use ultrasound analysis. This technique is able to detect damages at the earliest stages. This is related to the advantages and disadvantages, presented in table 4.1 based on [15].
For the specific application at Duyvis, the decision is made to focus on vibration analysis. Vibration analysis is the most common used condition monitoring technique for rotating equipment and has multiple application options available related to the different maturity levels.

| **Ultrasound** | **Vibration** | **Oil** | **Infrared** |
|---|---|---|---|
| *Advantages* | *Advantages* | *Advantages* | *Advantages* |
| - Early fault detection<br>- Large signal to noise ratio | - Reliable and standardized<br>- Reacts immediately to change<br>- Ability to detect damaged part | - Easy condition characterization<br>- Possible to detect damage type<br>- Possible to detect location of damage | - Standardized method<br>- Able to detect anomalous working area |
| *Disadvantages* | *Disadvantages* | *Disadvantages* | *Disadvantages* |
| - Expensive<br>- High sample frequency | - Expensive<br>- Intrusive<br>- Subject to sensor failure | - Expensive<br>- Late detection<br>- Difficult to apply to grease lubricated bearings | - Late detection |

Table 4.1: Advantages and disadvantages condition monitoring technique, based on [15]

The ultrasound technique was not desirable due to the difficulty of gathering the data with the ultrasound technique. To be able to use ultrasound, an expert must perform the measurements. At Duyvis, these experts are not available. One of the reasons Duyvis is changing its PdM program is to execute the program in-house to be more involved.
Oil analysis and infrared analysis are, in general, not the primary condition monitoring techniques in PdM programs. Due to the late stage of detection with these techniques. However, they might be an add-on for the primary technique.

### 4.1.2. Basis of vibration monitoring

Vibration monitoring is the condition technique that will form the basis of the PdM programs. In this section, the basis of vibration monitoring will briefly be explained. This information is required to make the other decisions regarding the PdM program.

SKF provided a guide on vibration diagnostics [38]. In this guide, vibration is described as the behaviour occurring due to a machine's mechanical components reacting to internal or external forces. All machines and mechanical components have vibrations, and the change in this vibration can indicate a problem.

In general, vibration is described using a mass-spring setup, figure 4.2. Moving the mass results in an oscillating movement. The oscillating movement over time forms a sine wave. When assessing vibration data, it is essential to take the amplitude, the size of the signal, and the frequency, the number of times a cycle occurs in a given period, into account.

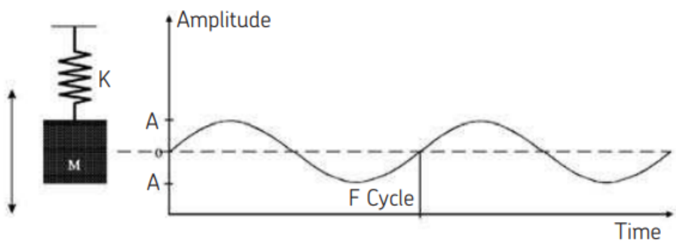



Figure 4.2: Mass spring example of vibration, [38]

Vibration has three different forms of measurement that can be used to determine the condition of an asset.
**Displacement:** The change in distance or position of an object relative to a reference point.
**Velocity:** The speed at which the distance is travelled.
**Acceleration:** The rate of change of the velocity.

The displacement, velocity and acceleration are mathematically related to each other. However, they are not three different names for the same thing. They are different characteristics. To detect the different measuements, different frequency levels are required. In general, displacement is measured below 10 Hz, velocity between 10 en 1000 Hz, and accelerations above 1000 Hz [10].

How is this information related to detecting bearing failure? Bearing failure will also result in vibrations. The amplitude of the vibration signal will indicate the severity of the damage, and the frequency of the vibration can be used to determine the type of damage.

As already discussed, bearing damage can result from different aspects and can be present on all the different parts of a bearing. Damage to the different parts of the bearing result in different frequencies, the bearing failure frequencies. There are four different failure frequencies [12, 18, 27, 38].

- $F_{ord}$ = BPFO = Frequency Outer Race Defect
- $F_{ird}$ = BPFI = Frequency Inner Race Defect
- $F_{bd}$ = BPF = Frequency Ball Defect
- $F_c$ = FTF = Frequency Cage

To determine these frequencies the use can be made of equations 4.2 to 4.4.

$$BPFO = RPM\frac{N_B}{2}(1-\frac{B_D}{P_D}cos(\beta)) \quad (4.1)$$

$$BPFI = RPM\frac{N_B}{2}(1+\frac{B_D}{P_D}cos(\beta)) \quad (4.2)$$

$$BPF = RPM\frac{P_D}{B_D}[1-(\frac{B_D}{P_D}cos(\beta)^2] \quad (4.3)$$

$$FTF = RPM\frac{1}{2}(1-\frac{B_D}{P_D}cos(\beta)) \quad (4.4)$$

Knowing the failure frequencies will give insight in the frequency range required for the sensing devise.

### 4.1.3. Vibration monitoring application

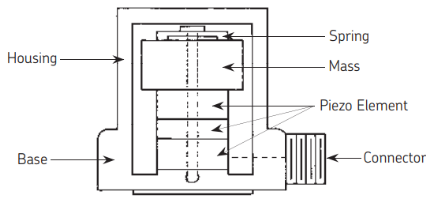
As already presented, three main measurements related to vibrations can be used to determine the condition of an asset. The different measurements are detected using different types of sensors.

Displacement is generally measured using a displacement probe or eddy probe. The displacement is measured as the movement of the shaft or rotor to the case of the asset. Displacement sensors are not commonly used since they can miss damage when the rotor and housing move due to the same vibration, resulting in a zero signal [38].

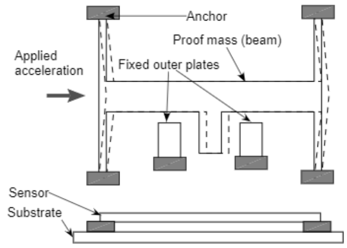
Velocity can be measured using a velocity sensor [38]. This sensor is very effective in measuring velocity. However, there is a downside, due to the, in general, low-frequency range, the sensor's data can only be used to gain insight into the velocity. It can not be used to determine the acceleration levels.

Due to the limitations of a velocity sensor and a displacement sensor, the accelerometer was introduced. An accelerometer will have a higher frequency range required to determine the acceleration. Unlike the other options, the accelerometer can be used to determine another measurement. The information gathered through the sensor can be integrated to get the velocity. The accelerometer is currently the most common sensor used in vibration monitoring applications[38].

The accelerometer can be a piezoelectric accelerometer or a MEMS sensor.
A piezoelectric accelerometer works with a mass and a piezoelectric element, figure 4.3a. A vibration will result in pushing the piezoelectric element into the mass, which produces an electrical output.
MEMS is microelectromechanical systems [22]. The MEMS sensor consists of a mass with plates that are supported by a mechanical system. A vibration will move the mass, resulting in a distance between the plates and the frame. The working of a MEMS sensor is presented in figure 4.3b



(a) schematic drawing of an accelerometer, [38]



(b) working principle MEMS sensor, [22]

The charge generated or distance between plates measured are transformed and amplified to be used for vibration analysis.

The different PdM programs will work with an accelerometer, depending on the configuration, either a MEMS or piezoelectric. Both can be used to measure the vibrations for the vacuum compressor pump.

But besides selecting the type of sensor it is important to take the following aspects into account.

- Vibration amplitude and frequency range
- Sensitivity
- Sampling frequency
- Measuring directions / axis
- size and Weight
- Application technique
- Environmental factors such as:
  - Temperature range
  - Humidity
  - Dust, cleaning agents or gasses
- Electrical power requirements, 24 volt or battery power
- Cost

These aspects are determined by following requirements and wishes. When there are no strict requirements on the aspects, a SWOT analysis will be used. A SWOT analyses the strength, weaknesses, opportunities and threats of a program. Two aspects related to the selection of a sensing device are difficult to determine. The sample frequency and the frequency range. The effect of these aspects on the overall cost-effectiveness of a PdM program is unclear. Both aspects can influence the ability of a PdM program to detect failure.

**Frequency range**
The minimum frequency range can be determined using the bearing damage frequencies. For the vacuum compressor pump the bearing failure frequencies are calculated and presented in table 4.2. The minimum frequency range for the sensing device should cover these failure frequencies. However, it is unclear what the effect of higher frequency ranges is on the cost-effectiveness. Bearing damage evolves over 4 stages, using the bearing failure frequencies, damage at stage 3 can be detected. Detection in less advanced stages requires a higher frequency level. The different frequency ranges are linked with the analysing technique and detect-ability, presented in section 4.2.

| Location frequency | 1: NU 208 ECP | 2: 3309 A |
|---|---|---|
| BPFO: Outer race | 279.7 Hz | 156.0 Hz |
| BPFI: Inner race | 404.0 Hz | 234.6 Hz |
| BPF: Ball | 259.7 Hz | 201.6 Hz |
| FTF: Cage | 20.0 Hz | 19.5 Hz |

Table 4.2: Failure frequencies bearings vacuum compressor pump

**Sample frequency**
The sample frequency represents the interval between samples. It presents how many times the data is gathered. The sample frequency is highly related to the ability to detect damage. With a higher sample frequency, the data is gathered more often, so more data is available. In general, more data means more insight, which means more accuracy. Nevertheless, it is essential to know that a higher sample frequency is only effective if there is time to assess the data.

Besides this, it is also essential to consider the type of failure assessed with the PdM program. If the PF curve of the failure is very steep, the time between detecting and failure is short. A high sample frequency is required to make sure the damage is detected in time.

The final aspect that is important when selecting a sampling frequency is the amount and quality of the data collected at one sample point. The type of data effect the amount of energy required to send the data from the sensing device to the computer.
Two devices of the same price can differ in sample frequency, affected by the type and quality of the data collected. If a sensor collects data in the frequency domain, the amount of energy required to send the data will be higher than a sensor that will only send a numerical value. Due to this, the second option will be able to collect and send the data more often.

Due to the relation between the sample frequency and frequency range, it is challenging to set requirements. It gets even more complicated when the relation of the sample frequency on the detect-ability is taken into account, discussed in the next section.

## 4.2. Data analysis

Besides collecting the data, it is also important to analyse the data. Analysing the data will give insight into the asset's condition and will indicate if there is damage. In some cases, it is possible to determine the cause of the damage and the evolvement rate of the damage.

Multiple analysing techniques can be used to analyse the data gathered in step 1 of the program. The technique used in a program is related to the configuration of the program. As already discussed, the data collected can have different qualities. Some analysing techniques require detailed quality data. The quality of the data is related to the sample frequency. Another aspect that influences the analysing technique is the type of data collected. A numerical value can only be used to plot trend-lines, while a time set of data can be used for more in-depth analysis.
The analysing technique influences the ability to detect different stages of bearing damage, which will be discussed later. First, some general information on 5 commonly used analysing techniques.

### 4.2.1. Analysing techniques.

There are multiple ways the data can be analysed. In paper [38] the 5 most common analysing techniques are presented. They are:

- Overall vibration analysis
- Time waveform analysis
- FFT spectrum analysis
- Envelope spectrum analysis
- SEE analysis

Below a short summary on the 5 analysing techniques. The information is based on [13, 18, 38].
**Overall Vibration Analysis**
The most simplistic form of analysis. It considers the total vibration energy measured within a frequency range. The results will be a numerical value that will be plotted over time in a trend-line. The trend-line is an effective and reliable method to determine if something is wrong with the asset. A trend-line can be used to determine if a value is changing over time. If the overall vibrations start to increase, it could be said that damage is occurring.

**Time waveform analysis**
The second technique is related to analysing a time waveform. A time waveform is a representation of raw data over a short period. An example of a time waveform of vibration data is presented in figure 4.4. The time waveform is not commonly used due to the difficulty of directly assessing the waveform. If it is used, it is always in combination with another technique.

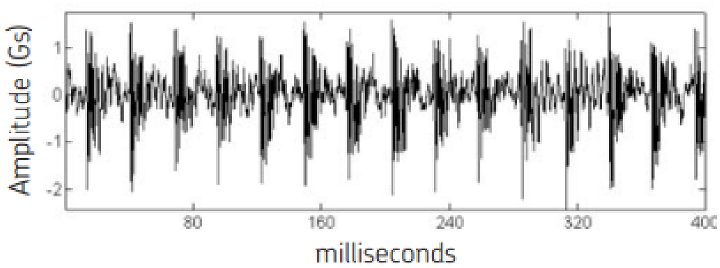



Figure 4.4: Time waveform vibration [38].

**FFT spectrum analysis**
FFT is fast Fourier transform. Non mathematically explained, FFT is a way of splitting a vibration signal in separate sine waves and plotting the amplitudes of the different frequencies. The result is a FFT spectrum. In figure 4.5 a generic vibration signal is transformed into a FFT spectrum.

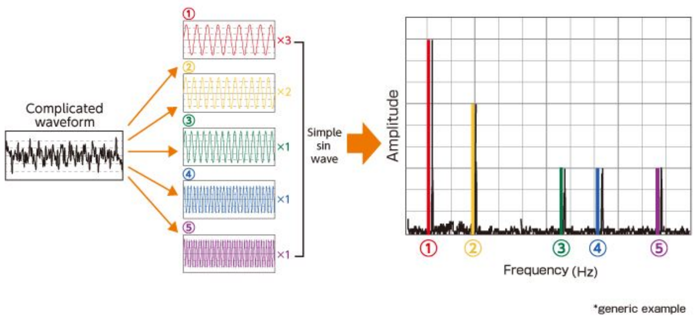



Figure 4.5: FFT transform of vibration signal [13]

The FFT spectrum can be used to provide information on the location of the problem and the severity. As already discussed, the different locations of bearing damage have their own failure frequencies. An increase of amplitude at these frequencies on an FFT spectrum can indicate increasing damage on this part. The rate the damage is increasing can be used to estimate the life left. The FFT spectrum can also be used to determine numerical values, which can be plotted as a trend-line.

**Envelop spectrum**
The fourth analysing technique is similar to the FFT spectrum, only more advanced. With envelope analysis, the signal is filtered to enhance the defect signal. If this is not done, the signal can get lost in the signals produced by rotating. Using envelop analysis will make it possible to detect a failure at a much earlier stage, but it does require higher frequency ranges.

**SEE analysis**
The final and most advanced analysis technique is SEE, spectral emitted energy technique. To be able to use this technique, the data has to be collected at a high-frequency range. The SEE technology is related to acoustic emission and might be better classified as an ultrasound condition monitoring technique. However, acoustic emissions can be presented as vibrations. Using this technique will make it possible to detect damage in the earliest stages.

### 4.2.2. Detect-ability

As already shortly introduced, the different analysing techniques can be related to the ability to detect the different stages of bearing damage. Bearing damage evolves over 4 stages. The different stages of bearing damage can be detected in different frequency ranges using different analysing techniques.

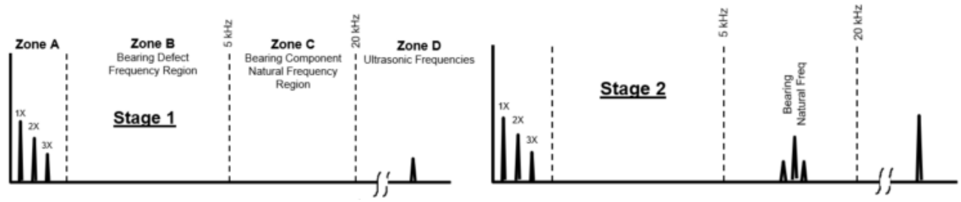
The pattern of the vibration changes as bearings deteriorate through different stages. These changes can be seen on a frequency amplitude plot. This plot can be divided in four different zones:

- **Zone A**: Machine rpm and harmonics zone
- **Zone B**: Bearing defect frequencies zone
- **Zone C**: Bearing component natural frequencies zone
- **Zone D**: High frequency detection zone

Spikes in the different zones can indicate different stages of bearing damage, information on the detection of the different failure stages is presented. This information is gathered from [12, 17, 26, 27]

**Stage 1**
At stage 1, damage starts to occur. The damage is minimal and not yet able to be detected by eye. However, the damage can be detected in the high-frequency detection zone, Zone D. A frequency range between 20 to 40kHz, is required to detect these damages [17]. In general, SEE analysis is used to detect damage in this zone. Figure 4.6a.

**Stage 2**
Stage 2, the damage is a little larger, still microscopic. Due to this, the frequencies will appear at a lower frequency level. Spikes now appear in zone C, and D. Detecting the failure in zone C requires the data to be analysed using the envelop spectrum method, which is generally related to high-frequency levels. Figure 4.6b



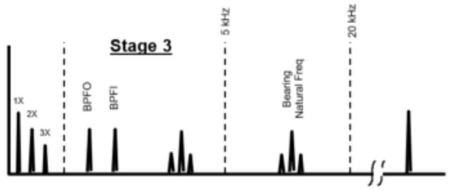

(a) Stage 1 detection [26]

(b) Stage 2 detection [26]

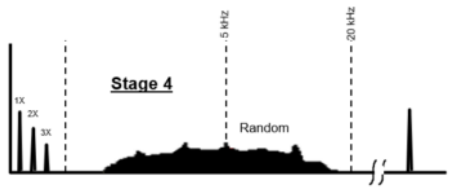
**Stage 3**
The damage on the bearing is now at a stage where initial spalling, flaking or cracking is occurring. Due to this, the bearing defect frequencies can be detected. They are present in zone B. Zone B can be detected with low-frequency sensors using the FFT spectrum or overall vibration. Figure 4.7a.

**Stage 4**
In the final stage, stage 4, the damage is very severe, resulting in random noise in all the different frequency zones. There are no specifics on the frequency range or analysing method used to detect a stage 4 damage. Figure 4.7b.

The frequency range in combination with the analysing method used in a PdM program will influence the detect-ability of the program. The detect-ability is the ability of a PdM program to detect the different stages of bearing damage. The relation between the frequency range, analysing method, and




(a) Stage 3 detection [26]




(b) Stage 4 detection [26]

detect-ability is presented in table 4.3. In general, it could be said that a higher frequency range with more advanced analysing methods will give the ability to detect damage earlier.
However, as already discussed, a higher frequency range and quality of data influence the sample frequency. The simulation cost model will be used to gain insight into the effect of sample frequencies and detect-abilities on the cost-effectiveness of a program.

| Damage stage | Detection zone | Analysing method | Frequency range |
|---|---|---|---|
| Stage 1 | D | SEE analysis | High (20 to 40 kHz) |
| Stage 2 | C | Envelop spectrum | Medium (up to 20 kHz) |
| Stage 3 | B | FFT spectrum/overall vibration | Low (up to 10 kHz) |
| Stage 4 | A,B,C,D | No requirements | no requirements |

Table 4.3: Requirements for detection of the damage stages

## 4.3. Decision making

The final step of a PdM program is decision making. The decision making is done based on the information on the assets condition. The data that is analysed will indicate the current state of the asset. Either no damage or the different stages of wear are detected. In the case of damage, an estimation of the life left in the bearing can be given. Related to the different stages of damage.

In general, the information on the condition of the asset is presented on a dashboard. The maintenance department uses this information to plan maintenance actions. The severity of the damage indicates the way the maintenance action should be planned. The severity of the damage is generally presented using alarm codes, Green: No damage, Yellow: minor damage(stage 2), Orange: larger damage (stage 3), Red: severe damage (stage 4).

The alarm codes presented on the dashboard by the PdM program will be used to make decisions on how the maintenance actions are planned. Because the different stages of damage refer to different amounts of life left in the bearing.
In this research, 3 different planning options are possible. The different options depend on the stage of the damage. The planning options influence the cost related to the maintenance actions.

- **OPM: Optimal Planned Maintenance**
  With OPM, the maintenance actions are planned most optimally. Possible when the bearing damage is detected in an early stage. It allows planning the maintenance actions at the most convenient time. Related to the cost and the life left in the bearing. The bearing should be replaced for as low as possible cost and with as low as possible life left. Besides this, it is required to gather information on the type of damage. The type of damage will make it possible to plan the maintenance according to the problem. This information can be gathered by using an envelop spectrum analysis.

- **PM: Planned Maintenance**
  The second type of planning is planned maintenance. The planning will start immediately when the damage is detected in a severe stage, level 3 or higher. The planning will be done according

to normal conditions and planned so that the maintenance activities will not influence the production. Due to the late detection, it is impossible to gather data to determine how fast the damage is evolving. The planning will start immediately. Due to this, it might be that the bearing is replaced with more useful life in it compared to the bearings replaced with OPM.

- **EPM:Express Planned Maintenance**
  If the bearing damage is severe or an unexpected breakdown has occurred, express planning might be required. Express planning will plan the maintenance activities using a faster planning time. However, this does come with extra costs, but this is advised to prevent long downtimes.

From the explanation of the different maintenance options, it can be concluded that the maintenance actions are related to the detect-ability and bearing condition at detection. For example, a PdM program that can only detect the damage in stage 3 will never advise on doing OPM. OPM requires detection of stage 2 damage.

In figure 4.8 an overview of the three maintenance planning options is presented. The information on the maintenance planning options will be used in the simulation cost model.

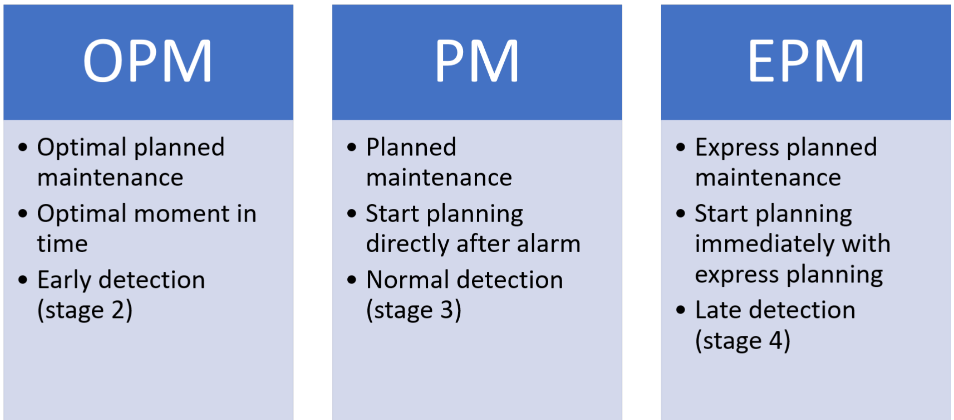



Figure 4.8: Overview maintenance planning options

## 4.4. PdM Program options

Using the information on the different steps of the PdM program and the focus point, it is time to narrow down the options.

The first step is to gather information on the different options available. This is done by participating in ConMon meetings. ConMon meetings are meetings with all the maintenance departments of the PepsiCo plants in Europe. During these meetings, experiences are shared, and sometimes presentations by suppliers are given. The ConMon meetings are set up to get insight into the applications at different plants and learn from each other. The information gathered in these meetings, the preference of Facta and the experience at other PepsiCo plants in the Netherlands has resulted in the decision to focus on the program options provided by SKF and Banner.

After making this decision, the options available by these companies are analysed. Information on the different options is gathered through meetings by both companies.

Besides using the information to gain insight, the following requirements are used to make decisions. related to the information provided in section 3.5

- The program should have a maturity level 2, 3 or 3 plus
- The investment cost of the PdM programs should be below €2000 for a vacuum pump.
- the program focuses on bearing damage using vibration analysis.
- Duyvis in-house mechanics must be able to use the program.

Finally, using all the information gathered, the requirements, wishes, and preferences, the following 4 programs are selected. These 4 programs and the current situation are analysed using the simulation tool. The information provided on the different programs have been collected through multiple meetings with the suppliers of the programs.

**Program 1: Current situation**
The first program is the current situation. The current situation is analysed to see the impact of changing the PdM program. The current situation is a level 2 program. The discontinuous inspections are performed by the service partner Facta. During the inspections, the data is gathered using a Micrologue. A Micrologue has a high-frequency range. During the inspections, large amounts of data are collected. The data is analysed at Facta by experts. The detect-ability of PdM program 1 is, due to these aspects, high. All 4 stages of damage can be detected. The inspections are performed every 4 months.

**Program 2: Level 2 in-house application Quick Collect**
Program 2 is a different application of a level 2 program. The program is still discontinuous. But the inspections are now performed by in-house mechanics. Switching the way the inspections are executed made it possible to increase the frequency. The inspections will be done every 2 months. But the in-house operation also comes with a downside. The Quick Collect has a lower frequency range resulting in a lower detect-ability. The Quick-Collect can detect stage 2, 3 and 4 damage. The data collected is presented as a trend line to get insight into the general vibration data. But it is also possible to use an envelop spectrum analysis. In general, the in-house staff will analyse the data unless there is a suspicion of damage. In these cases, the experts at Facta will have a look. The quick collect is a handheld sensor that can be placed on an asset. Detection plates are used to make sure the measurements are always taken in the same location. Due to the portability of the Quick Collect, it can easily be used for a large number of different assets.

**Program 3: level 3 online continuous monitoring system IMx1**
Program 3 is an online continuous monitoring system of maturity level 3. The IMx1 application is provided by SKF and has a sample frequency of every 3 hours. The data collected every three hours is used to present a trend line. Every week higher quality data is collected, which could be used to do an envelope spectrum analysis. combining these aspects makes the IMx1 able to detect stages 2,3, and 4 damage. The IMx1 is an application that uses a wireless sensor, which is connected to a gateway. The gateway will push the data into a cloud where it can be extracted. Either by Facta to perform a more in-depth analysis or presented on a dashboard that Duyvis will use to get insight into the asset's condition. If the in-house staff notices a deviation in the trend or spectrum, the experts at Facta will be asked to do a more in-depth analysis.

**Program 4: level 3 online continuous monitoring application Banner**
Besides the online option provided by SKF, there is also an option provided by Banner. The application provided by Banner is also a level 3 online continuous monitoring system but differs in the sample frequency and detect-ability. The sample frequency of the Banner application is very high. Every 5 minutes data is collected. But as already explained, to have a higher sample frequency, the quality of the data will be lower when the price is similar. The Banner program is due to the lower quality of data only able to detect stage 3 and 4 damage. The banner system is applied in similar ways as IMx1.

**Program 5: Combination of inspections Quick-Collect and online monitoring Banner.**
Program 5 is a program that combines the high sample frequency of the Banner application with the higher detect-ability options of the Quick Collect. Related to a level 3 plus option. Level 3 plus is the new maturity level that combines multiple PdM programs. The Banner and Quick-Collect application will, in both cases, be similar, as already explained. The only difference is that the sample frequency of the Quick Collect will be reduced to 4-month intervals.

**Overview**
To summarise. In table 4.4 the different programs are presented. The programs differ in their maturity level, sample frequency and the detect-ability. The detect-ability is related to the ability to detect the different stages of bearing damage. The detect-ability of a PdM program is related to the ability to detect different zones, related to the analysing technique and the frequency range of the application.

| Program | Name | Level | Sample frequency | Detect-ability* |
|---|---|---|---|---|
| 1 | Current situation | 2 | 3 to 4 Months | 1,2,3,4 |
| 2 | Quick Collect (QC) | 2 | 1 to 3 Months | 2,3,4 |
| 3 | SKF IMX1 | 3 | 3 hours | 2,3,4 |
| 4 | Banner | 3 | 5 min | 3,4 |
| 5 | QC+Banner | 3+ | 1-3Month/5 min | 2,3,4 |

* The ability to detect the 4 different stages of bearing damage.

Table 4.4: PdM programs

## 4.5. Conclusion

Chapter 4 includes the decisions on the different aspects of a PdM program, answering the third sub-question. It can be concluded that two aspects are difficult to determine and should be included in the program analysis. These are the sample frequency and detect-ability, and both aspects influence the ability of programs to detect damage. 4 programs and the current situation will be analysed on their cost-effectiveness. The 4 new programs have different sample frequencies and detect-abilities and can be applied to the vacuum compressor pumps at Duyvis. The 5 programs are 1)Current situation, 2)Quick Collect, 3)IMx1, 4)Banner, and 5) combination of Quick Collect and Banner.

# 5
# Simulation cost Model

As presented in the previous chapter, there are 5 different PdM program options. These options could be cost-effective for the vacuum compressor pumps at Duyvis. However, there are still uncertainties about which one would be the most cost-effective. The main differences between the options are the maturity levels, the sample frequency and the detect-ability. Analysing the impact of these aspects will give insight in the cost-effectiveness of the programs.

As already discussed, cost-effectiveness is related to two KPIs, the overall cost and the reliability. Assessing these aspects will be done with a simulation cost model. The simulation cost model will be used to get insight into the overall cost of the different programs. But also provide insight into the number of unexpected breakdowns, the maintenance planning methods used and the time available for planning.

In this section, the model will be introduced. First, the simulation technique is introduced, followed by an overview of the model. The simulation cost model consists of a simulation model in combination with a cost model. Both will be introduced as well as the input, output and assumptions of the model. Finishing with an overview of the application of the different PdM programs on the model.

## 5.1. Simulation technique

To analyse the cost-effectiveness of different PdM programs, a simulation tool will be used. A simulation is an imitation of the dynamics of a real-world process or system over time [19]. Using a simulation provides the possibility to analyse complex situations with fewer assumptions [2]. A simulation tool uses a simulation technique to be able to analyse complex situations. In figure 5.1 an overview of the classification of different simulation techniques is presented.

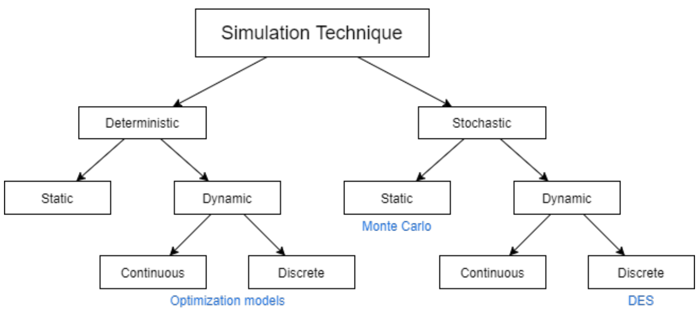



Figure 5.1: Simulation technique classification overview [20]

The first categorisation is stochastic vs deterministic simulation techniques. Stochastic simulation techniques are used when the situation that is being simulated consists of random parameters. Whilst with a deterministic model, the behaviour is entirely predictable and the input is set. The second category is static vs dynamic. A model that evolves over time is a dynamic system, while a static system only addresses one point in time. The last categorisation aspect is the differentiation between discrete vs continuous models. Discrete models only assess the variables at discrete points in time, so only set moments in time are simulated. Whilst continuous models evaluate the variables at every time point, so continuously. In figure 5.2 a schematic view of the difference between discrete and continuous is presented.

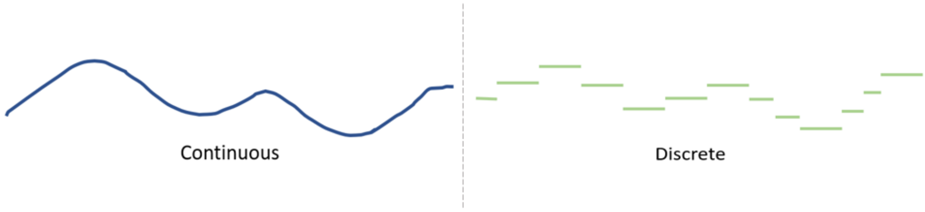



Figure 5.2: Continuous vs. Discrete

**Simulation technique selection**
The overview presenting the different simulating techniques is used to select a simulation technique for the simulation cost model. The main goal of the simulation cost model is to assess the cost-effectiveness of PdM programs. Focusing on the overall cost and reliability.

The PdM programs have different sample frequencies and detect-ability options. The effect of these aspects on the cost-effectiveness is uncertain. Which makes it challenging to use a deterministic simulation. A stochastic simulation technique is more suitable for the simulation cost model due to the uncertainties in the parameters.

The next decision is between a static or dynamic simulation technique. The PdM programs will be analysed over 4 years, the expected application period of the PdM programs. The cost-effectiveness is analysed over the 4 years to get insight into all the aspects that can influence the overall cost and reliability over this period. It will give a complete picture of the cost-effectiveness. Resulting in a dynamic simulation.

The final decision is between continuous or discontinuous simulation. Continuous simulation might be able to give a complete picture of the situation. However, this is not required for analysing the cost-effectiveness of the PdM programs. To analyse the cost-effectiveness of the programs only the aspects related to the program's application and ongoing operation is interesting. For instance, The data gathering and the effect this has on the type of maintenance planning used. It is not necessary to analyse the model in between the sample collections. Due to this, the decision is made to use a discrete event simulation (DES).

A DES is a modelling technique that only assesses the situation when there are changes in the model. It creates a line of events that are waiting to happen. The simulation moves through the line of events without simulating the time in between the events [2]. In the simulation cost model, the line of events will be related to the data gathering at the sample frequencies. If damage is detected, the maintenance actions will be added to the list of events. When the maintenance actions are performed depends on the type of maintenance planning used. Using these aspects will give insight in the overall cost and reliability of the programs.

## 5.2. General built-up

The simulation cost model consists of two parts. The DES model will be combined with a cost model to get insight into the cost-effectiveness aspects. In figure 5.3 the interaction between the DES model and the cost model is presented. The DES model will be used to simulate the different programs applied to a vacuum compressor pump. The results of the DES model will partially give insight into the reliability but will also be used as input for the cost model. The cost model will be used to determine the overall cost related to the PdM programs. The input and output of the model will be discussed later. But first, some information on the built-up of the DES and cost model.

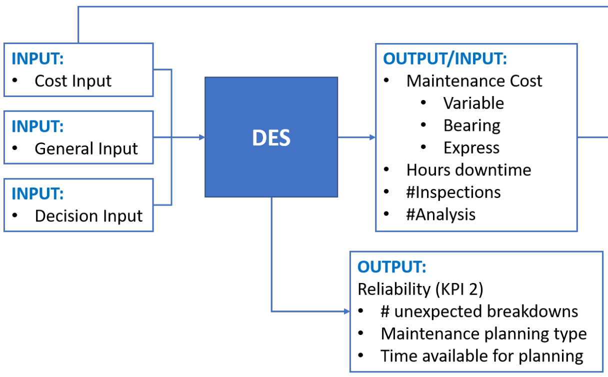



Figure 5.3: Interaction DES and cost model

## 5.3. Discrete event simulation Model

In this section, information is provided on the way the DES model is built-up. The DES model is used to simulate the application of the PdM programs on the vacuum compressor pump.

### 5.3.1. Components

The DES model consists of three components to simulate the situation, 1) the machine, 2) the PdM program and 3) the maintenance actions. These components will all have their own actions, input and output. But they also interact with each other, this is graphically presented in figures 5.4.

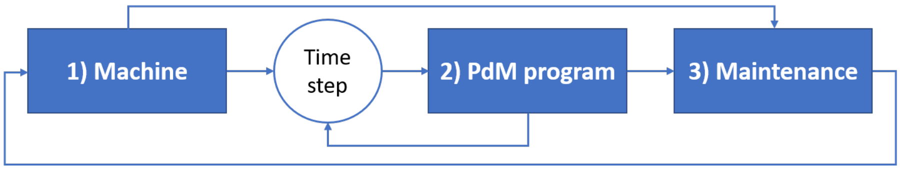



Figure 5.4: interaction components DES model

The different components are used to present different aspects related to the application of the PdM program. Below, an overview of the input, actions and output of the different components is presented.

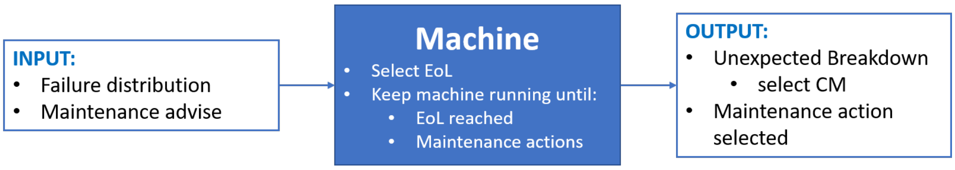



Figure 5.5: Input, action, output machine component

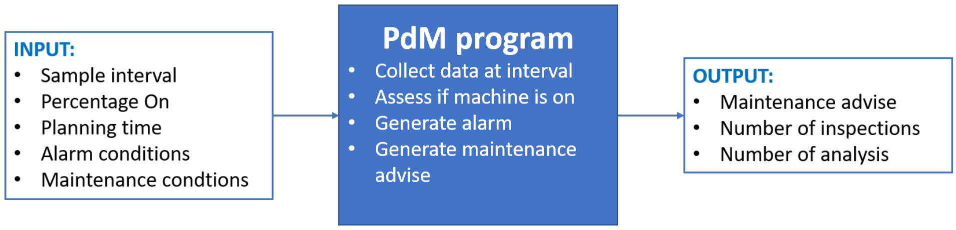



Figure 5.6: Input, action, output PdM component

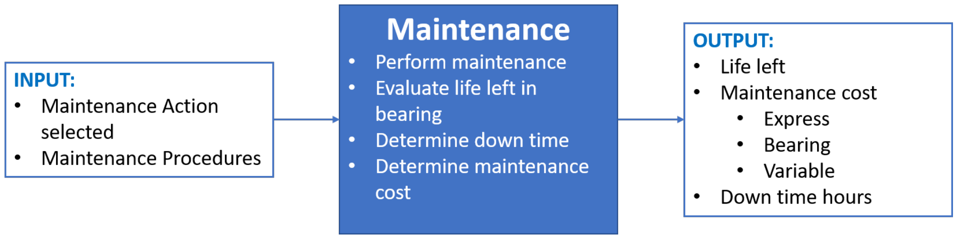



Figure 5.7: Input, action, output Maintenance component

## 5.3.2. Overview DES model

To create a clearer picture of the simulation model the following flow-diagram is used, figure 5.8. In appendix D a pseudo-code of the simulation model is presented.

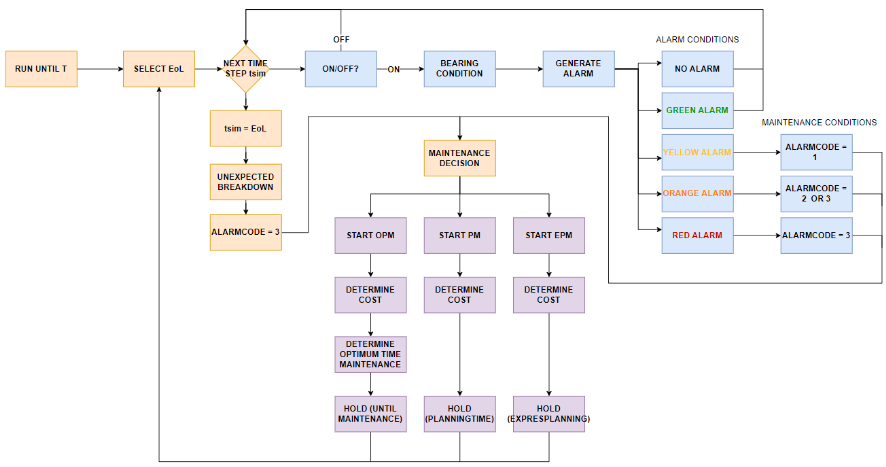



Figure 5.8: Flow diagram simulation model

The DES model runs for 4 years and starts with the machine component. The machine component is used to activate the machine for a certain amount of time, related to a selected end-of-life time (EoL). The EoL is selected using the probabilities in the failure distribution. The machine keeps running until this EoL is reached, resulting in an unexpected breakdown. Another option is that the machine is interrupted due to an alarm, the alarm results from the PdM program. The PdM program works by collecting data at the sample frequency interval. The PdM program will only collect the data if the asset is on. The data collected will give insight into the condition of the asset. This condition will be used in combination with alarm conditions to determine which maintenance planning should be used.
Depending on the type of alarm, generated by the PdM program or due to an unexpected breakdown, a maintenance planning is selected. The three options for maintenance plannings are all combined in the maintenance component. The three options are express planned maintenance (EPM), planned maintenance (PM), and optimal planned maintenance (OPM). The maintenance planning option selected will be used to update the information required for the overall cost. When the maintenance actions are done, a new EoL will be selected, and this will be repeated until the 4 years are reached.

### 5.3.3. Alarm conditions

As already presented, the DES model uses alarm conditions. The alarm conditions are used in combination with the condition of the asset. The condition of the asset is determined using the following equation.

$$BearingCondition = EoL - env.now \tag{5.1}$$

The condition of the asset indicated the amount of life left in the asset. It is a function of the EoL selected and the current time related to the sample frequency. The amount of life left in a bearing can be related to the different stages of bearing damage, which influence how the maintenance actions should be planned. The ability to detect the different stages of damage is related to the detect-ability of the PdM programs. This relation is used to form the alarm conditions, graphically presented in figure 5.9.

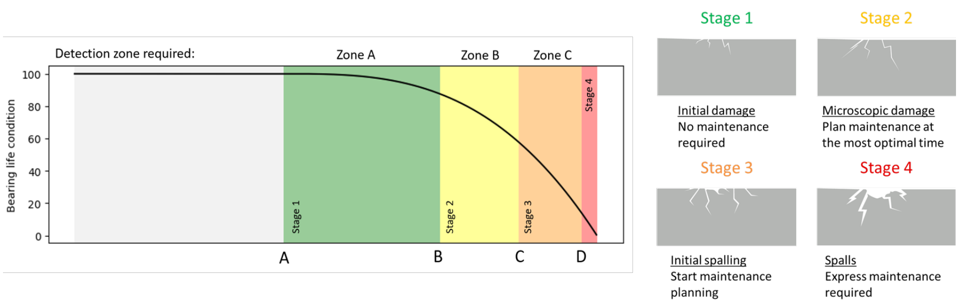



Figure 5.9: Graphic representation of alarm condition relation

The different stages of damage result in different alarm codes. To generate the alarms the following alarm conditions are used, 5.2.

$$Alarm = \begin{cases} NoAlarm & \text{if} \quad BearingCondition \geq A \\ Green & \text{if} \quad A > BearingCondition \geq B \\ Yellow & \text{if} \quad B > BearingCondition \geq C \\ Orange & \text{if} \quad C > BearingCondition \geq D \\ Red & \text{if} \quad BearingCondition < D \end{cases} \tag{5.2}$$

The numerical values presented in the figure and in the alarm conditions can be based on two different aspects. Either on information provided in the literature or information used in practice. In the literature, the different bearing damage stages are generally related to a percentage of life left. The other option is to base the numerical values of the alarm conditions on the information used in practice. Currently, inspections are planned based on assumptions related to the failure behaviour of bearings of rotating assets. Facta, the service partner of Duyvis, uses a three-month interval. The three-month interval is used because this results in the highest possibility to detect damage. This information will be combined with the ratios used in the literature. The numerical values are presented in table 5.1.

| **Based on** | **A** | **B** | **C** | **D** |
|---|---|---|---|---|
| *Literature* | 20% life left | 10% life left | 5% life left | 1% life left |
| *Practice* | 5 Months | 2.5 Months | 1.25 Months | 0.25 Months |

Table 5.1: numerical values alarm conditions

The main difference between the two options is related to the damage evolvement. In the case of alarm conditions based on practice, the damage will always evolve at the same rate. In contrast, alarm conditions based on literature result in variable damage developments rates. In this case, the evolvement of the damage is related to the selected EoL. Selecting the most representative option for the situation is difficult, in combination with the unknown effect on the cost-effectiveness of the options, the decision is made to use both options to analyse the PdM programs.
The alarms are related to the condition of the asset, which is related to the different stages of bearing

damage. Due to this, the alarms will be used to decide on the maintenance planning that should be used. The simulation cost model uses maintenance conditions to select the most suited maintenance planning option. The maintenance conditions are presented in equation 5.11.

$$MaintenanceAction = \begin{cases} OPM & \text{if} \quad \text{\#YellowAlarm } \geq X \text{ and } \text{\#Spectrum } \geq 1 \\ PM & \text{if} \quad \text{OrangeAlarm + Planning Time } < \text{ EoL} \\ EPM & \text{if} \quad \text{OrangeAlarm + Planning Time } \geq \text{ EoL} \\ EPM & \text{if} \quad \text{RedAlarm} \\ EPM & \text{if} \quad \text{Unexpected Breakdown} \end{cases} \tag{5.3}$$

In the maintenance conditions, the X at the OPM condition is related to the required number of data samples. An X amount of data samples is needed to determine how fast the damage is evolving. This information is required to plan the maintenance actions at the most optimal time, OPM.

## 5.4. Cost Model

Besides the DES model also a cost model is used. The cost model uses cost input and the output of the DES model to determine the overall cost, one of the KPIs. The cost model is built-up of three cost categories, 1) Cost related to maintenance($C_M$), 2) Cost related to unplanned downtime ($C_{DT}$) and 3) cost related to the PdM program ($C_{PdM}$). These different cost categories will be introduced below.

But first, another aspect that should be mentioned. Besides the three cost categories mentioned above, another cost aspect is indirectly taken into account in the simulation cost model. This is the cost related to the life left in the bearing at the time of replacement. It is important not to replace a bearing too early. This aspect is taken into account by simulating the situation over an extended time. Replacing the bearing too early increases the possibility to have another failure. An increase in failures and maintenance actions will increase the overall cost.

### 5.4.1. Maintenance cost ($C_M$)

The first category is the maintenance cost, which is related to the maintenance activities. Equation 5.4 presents the equation used to determine the maintenance cost. The information related to the maintenance actions is provided by Mitch Zonneveld from Facta and Martin Franssen from Busch.

$$C_M = C_{Fixed} + C_{Variable} + C_{Bearings} + C_{Express} \tag{5.4}$$

In this equation, $C_{Fixed}$ is related to the fixed cost for servicing the vacuum compressor pump. When bearing damage is detected, and the decision is made to perform maintenance activities, the machine will be subjected to a standard revision program. Which includes an initial check, cleaning, and refitting new parts. The maintenance is done at an external workshop. Due to this, the machine has to be transported from and to Duyvis. These costs are the basis and do not depend on the time of detection.

The second aspect, the $C_{Variable}$, is the cost related to the secondary damage. If a bearing is damaged, this can result in damage to other parts of the machine. The amount of damage and if secondary damage will occur depends on the time of detection. The detection time relates to the stage of the bearing damage. The variable cost will be added if the stage of the damage is so severe that it could result in secondary damage.

The third aspect is the cost for the bearings, $C_{Bearings}$. Detecting stage 1 or 2 damage makes it possible to analyse which bearing is damaged. Due to this, the cost related to the purchase of the bearings can be lower. The final aspect of the cost model is the cost for express delivery of the bearings, $C_{express}$. If the damage is detected late, it might be necessary to use express delivery to reduce the time required to plan the maintenance actions. However, this does come with extra costs.

### 5.4.2. Down Time Cost ($C_{DT}$)

The second aspect that will be taken into account is the cost related to unplanned downtime of the asset, $C_{DT}$. The downtime of an asset is the time when the asset can not operate due to damage or maintenance activities. The downtime of an asset can be divided into planned or unplanned downtime. The planned downtime is due to maintenance actions, while the unplanned downtime occurs when the asset fails unexpected or when the maintenance actions are not planned in time. In this research, only unplanned downtime will be taken into account. The planned downtime is not considered because it will be the same for all the different PdM programs. The equation used for this aspect is presented below.

$$C_{DT} = \#HourDT * C_{DTHour} \tag{5.5}$$

In this equation, the number of hours the machine is down, $\#HourDT$ is multiplied by the cost per hour downtime, $C_{DTHour}$. The number of hours will result from the simulation model whilst the cost for an hour downtime is one of the input factors.

### 5.4.3. PdM program costs ($C_{PdM}$)

The third aspect of the overall cost is the cost related to the PdM program, $C_{PdM}$. The cost of a PdM program is divided in CAPEX and OPEX costs and these differ per program. To calculated $C_{PdM}$ equation 5.6 is used.

$$C_{PdM} = CAPEX_{PdM} + OPEX_{PdM} \tag{5.6}$$

The $CAPEX_{PdM}$ refers to the cost related to the investment of the PdM program []. The investment of the hardware is taken into account in this simulation model. $OPEX_{PdM}$ refers to the cost related to the day-to-day operation of the PdM program []. Multiple aspects can be taken into account when referring to the OPEX. In this research, three different aspects are taken into account.

1. The cost related to the maintenance of the program, for instance, the cost for new batteries.
2. The cost for collecting the data, related to the number of samples taken.
3. The cost related to analysing the data, a function of the times the data is analysed by external experts.

Combining these aspects results in equation 5.7.

$$OPEX_{PdM} = C_{maintenancePdM} + \#Inspections * C_{Inspections} + \#Analysis * C_{Analysis} \tag{5.7}$$

### 5.4.4. Overall cost model

To summarize the following cost model will be used.

$$\begin{aligned} Cost &= C_M + C_{DT} + C_{PdM} \\ C_M &= C_{Fixed} + C_{Variable} + C_{Bearings} + C_{Express} \\ C_{DT} &= \#HourDT * C_{DTHour} \\ C_{PdM} &= CAPEX_{PdM} + OPEX_{PdM} \end{aligned}$$

## 5.5. Input & Output

As already presented in section 5.2 the simulation cost model requires input to be able to simulate the situation, which will be used to provide output. The output will then be used to give insight into the cost-effectiveness of the PdM programs. In figure 5.10 the input and output related to the simulation cost model is presented. The input is divided into three different categories, 1) general input: which stays the same for all the PdM programs, 2) decision input: related to the detect-ability and sample frequency of the PdM programs and 3) cost input: related to the 3 categories of the cost model.
The output of the simulation cost model is related to the two KPIs, which are used to get insight in the cost-effectiveness. The input and output will be discussed in this section.

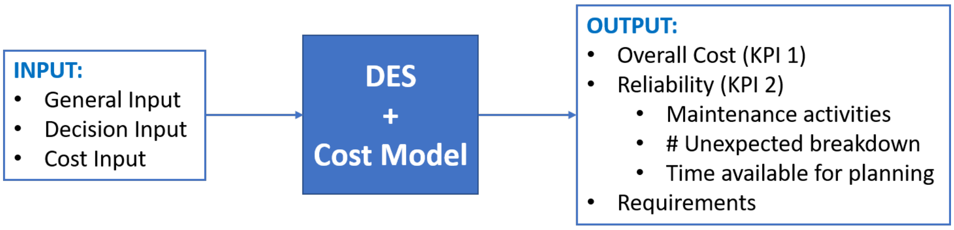



Figure 5.10: Overview input and output of simulation cost model

### 5.5.1. General Input

This first section will present the general input of the model. The general input stays the same for all the PdM programs.

**Simulation Time**

The simulation time is the total time that is simulated. In this research, the decision is made to simulate 4 years. 4 years is selected because it is expected that after 4 years, a new program will be introduced. Probably with more advanced techniques related to a level 4 maturity.

**Random-Seed and Repetitions**

A random seed will be used to make the simulation repeatable. The random seed will change according to the repetitions done. So iteration 1 will have random-seed = 1 etc, iteration 2 will have random-seed = 2... A random seed is used to make sure the same random variables will be used every time the simulation is repeated. Repetitions are used to analyse the cost-effectiveness of a program over several different situations. 500 repetitions will be used because with 500 repetitions, the EoL selected will clearly represent the failure distribution.

**ON/OFF conditions**

As already discussed in section 3.2.2 the machine has a discontinuous operating profile. The discontinuity of the asset might affect the amount of data that can be used. Inspections can be planned in such a way that the machine is always on when it is inspected. However, when the data is collected using an online monitoring tool, the sample time is determined beforehand. This could result in data that is not useful because the asset was OFF at the time of sampling. A lower number of useful data samples can have a high impact on the detect-ability of the different PdM programs.

This aspect is added to the simulation cost model by including the ON/OFF ratios of the assets. The ON/OFF ratios are determined by analysing the operation profile. There are 4 different ON/OFF ratios related to the 4 different vacuum compressor pumps. The following ON/OFF percentages are determined: 49.9/50.1, 10.7/89.3, 7.2/92.8, 42.8/57.2. The effect of the discontinuous operating profile of the different pumps on the cost-effectiveness is difficult to determine. However, it is an important aspect when selecting a PdM program. The PdM program selected has to be cost-effective for all 4 vacuum pumps. The effect of the ON/OFF ratios will be analysed to get a complete picture of the situation before selecting the most cost-effective option.

**Failure distribution**
The machine component of the DES model selects an EoL from a failure distribution. The failure distribution is related to the asset and presents a probability that the asset will fail at a certain time. As presented in section 3.3.2 there is some information that can be used to form a failure distribution. Using the limited information available, the following distribution is formed, figure 5.11. The distribution is a combination of 1) Failures due to infant mortality related to poor manufacturing. 2) Failures due to improper handling and lack of maintenance, based on the guarantee period and 3) Failures due to old age. The exact shape of the failure distribution was difficult to determine, but Wout de Clerck from Atlas Copco confirmed that this distribution looks representative.

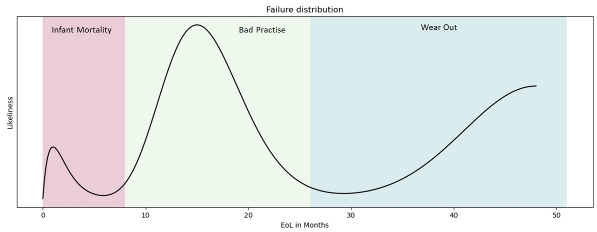



Figure 5.11: Failure distribution of the vacuum compressor pump

One important assumption is made regarding the failure distribution. In this distribution, the probability of a failure within the simulation time of 4 years is 100%.
The failure distribution presented above is based on information provided by Atlas Copco, but it can also be discussed that other distributions are possible due to the lack of factual information. The decision is made to focus on the already presented failure distribution and the following 6 options. The 6 options are related to the information provided but only take certain aspects into account.

1. **Random Failure:** Due to the high levels of uncertainty related to the failure behaviour of the pump, it could be said that the failure distribution is random.
2. **Wear Out:** The probability that the asset will fail will increase with time. Related to old age.
3. **Bathtub:** A combination of infant mortality with wear out damage.
4. **Short:** The asset will fail either to infant mortality or due to bad practice related to the guarantee period.
5. **Partially failure:** The standard failure distribution, but the distribution is now spread over 10 years.
6. **No failure:** The asset will not fail within the simulation period

The first 4 distributions all use a 100% probability that the asset will fail within the simulation time of 4 years. With the last two options this is not the case. The effect of the different distributions on the outcome of the simulation model should be assessed.

**Planning Time**
Planning time is the time required for planning the maintenance actions. Information provided by Mitch Zonneveld from Facta was used to determine the planning time. In general, the optimal planning time for Facta to schedule maintenance actions is 14 days. In the case of express planned maintenance, express planning will be used this is 3 days. 3 days is the minimum time required to make the asset ready for maintenance actions and order the bearings.

**Maintenance Time**
Besides the time required to plan the maintenance activities, there is also the time to perform the maintenance actions, 5 to 7 days. One day for dismounting the asset and transporting it to Facta, 3 to 5 days throughput time and 1 day for mounting the asset back in place. The time the asset is being maintained means the production capacity at the plant is reduced by 60%. However, the effect of performing the maintenance activities will be the same for all the PdM programs. Due to this, the decision is made to only focus on the time required to plan the maintenance actions.

**Overview general input**
In the table below an overview of the general input is presented.

| Input | Value |
|---|---|
| ON/OFF condition | 0.3 to 1 |
| Simulation Time | 4 years |
| Planning time | 14 days |
| Express planning time | 3 days |

Table 5.2: General Input

### 5.5.2. Decision Input

The second category is the input related to decision making. As already presented, the simulation model works with alarms based on the asset's condition to select a certain maintenance planning type.

**Alarm conditions**
As already discussed the alarm conditions are related to the stages of bearing damage. The alarm conditions depend on the PdM program. The PdM programs have different detect-abilities. The detect-ability is the ability to detect the different stages of damage, which are used in the alarm conditions. Below the alarm conditions for the PdM programs are presented.

**Alarm conditions PdM program 1: Current situation**
Able to detect damage of in all zones, so able to detect all four stages of damage.

$$Alarm = \begin{cases} NoAlarm & \text{if} \quad BearingCondition \geq A \\ Green & \text{if} \quad A > BearingCondition \geq B \\ Yellow & \text{if} \quad B > BearingCondition \geq C \\ Orange & \text{if} \quad C > BearingCondition \geq D \\ Red & \text{if} \quad BearingCondition < D \end{cases} \tag{5.8}$$

**Alarm conditions PdM program 2: Quick Collect (QC) and PdM program 3:IMx1**
The detect-ability of PdM program 2 and 3 are the same, due to this they use the same alarm conditions. Both are not able to detect damage of stage 1, related to the green zone. The green alarm option is removed and the No alarm condition is adjusted.

$$Alarm = \begin{cases} NoAlarm & \text{if} \quad BearingCondition \geq B \\ Yellow & \text{if} \quad B > BearingCondition \geq C \\ Orange & \text{if} \quad C > BearingCondition \geq D \\ Red & \text{if} \quad BearingCondition < D \end{cases} \tag{5.9}$$

**Alarm conditions PdM program 4:Banner**
The banner application is only able to detect stage 3 or 4 damage. Due to this only the orange and red alarm are possible. The no alarm condition has again be adjusted.

$$Alarm = \begin{cases} NoAlarm & \text{if} \quad BearingCondition \geq C \\ Orange & \text{if} \quad C > BearingCondition \geq D \\ Red & \text{if} \quad BearingCondition < D \end{cases} \tag{5.10}$$

**Alarm conditions PdM program 5:Combination QC and Banner**
PdM program 5 is a combination of PdM program 2 and 4. The alarm conditions are related to the program used to collect the data. So, if the data is collected using the QC the alarm conditions of PdM program 2 will be used.

In general, it is important to note that the alarm conditions for *No Alarm* change according to the maximum detect-ability of the PdM program. Damage above this limit will not be detected, resulting in *No alarm*. The detection zones that cannot be detected with the PdM program will be removed from the alarm conditions. As already presented the numerical values of the alarm conditions can be based on information provided in the literature or on information used in practice. The numerical values per option are provided in table 5.1.

**Maintenance conditions**
The next step is to use the alarm conditions to define the way the maintenance actions are planned. As already presented the following maintenance conditions will be used.

$$MaintenanceAction = \begin{cases} OPM & \text{if} \quad \text{\#YellowAlarm } \geq X \text{ and \#Spectrum } \geq 1 \\ PM & \text{if} \quad \text{OrangeAlarm + Planning Time } < \text{ EoL} \\ EPM & \text{if} \quad \text{OrangeAlarm + Planning Time } \geq \text{ EoL} \\ EPM & \text{if} \quad \text{RedAlarm} \\ EPM & \text{if} \quad \text{Unexpected Breakdown} \end{cases} \tag{5.11}$$

One of the aspects that required input is X, the number of yellow alarms. X indicates the number of data samples, which will be sufficient to determine the evolvement rate of the damage. An assumption will be made that this is 10 samples.

**Sample frequency**
The sample frequency is an aspect that is different for the PdM programs and also influences the decision making. The sample frequency represents how often the data is collected, presented as a time between samples. The number of samples taken can influence the ability to detect the different stages of damage in time. The sample frequency is partially related to the maturity levels of the PdM programs. The maturity levels indicate if the program is continuous or discontinuous.

With a continuous program, the time between samples is short. In the case of PdM program 3, which uses the IMx1 application, samples are collected every 3 hours. In the case of the Banner application, used in programs 4 and 5, the samples are taken every 5 minutes. The sample frequency is generally set for online conditions monitoring applications; it depends on the program's configuration.

In the case of a discontinuous program, the data is collected through inspections. Due to this, the time between the inspection can easily be adjusted. The interval between inspections can influence the cost-effectiveness of the program. In general, it could be said that the reliability will increase when the time between samples is reduced. But this could come with higher costs.
Besides these aspects, it is essential to consider the time required for collecting and analysing the data. This aspect is not taken into account in the simulation model but influences the possibilities for the inspection frequency. In the case of PdM program 1, the inspections are performed by Facta. Increasing the sample frequency will increase the reliability but also the cost. Also, the time to analyse the data is exceptionally long due to the amount of data collected per inspection. Currently, the inspection is done every 4 months, but this used to be every 3 months. The influence the switch has on the cost-effectiveness is uncertain.
In the case of PdM programs 2 and 5, the inspections are performed by in-house mechanics using the Quick-Collect. Because the inspections are performed in-house, there is more flexibility in the frequency of the inspection. Nevertheless, it should be kept in mind that mechanics need time to perform the inspections and analyse the data while also performing their other tasks. Due to this, the inspection interval can not be below once a month, and a longer time between inspections is desirable.

In table 5.3 the time between samples related to the PdM programs is presented. The impact of the different sample frequencies on the cost-effectiveness of the PdM program is uncertain and should be analysed.

| PdM program | time between samples |
|---|---|
| 1: Facta | 3 or 4 months |
| 2: Quick-Collect | 1,2,3,4 or 6 months |
| 3: IMx1 | 3 hours |
| 4: Banner | 5 minutes |
| 5: Banner and Quick-Collect | 5 minutes and 1,2,3,4 and 6 months |

Table 5.3: Sample frequencies related to PdM programs.

### 5.5.3. Cost input

The final category is the input related to cost. The overall cost is a function of three different categories already introduced. In this section, it is discussed how the different aspects are incorporated in the simulation cots model. More information on the cost aspects is presented in appendix E.In information on the cost input is collected through meetings with contact persons form Facta, SKF, Turck/Banner, Busch and Duyvis.

**Maintenance cost**

As already presented, the maintenance cost is built up of four different aspects. The first is the fixed cost. Facta has been consulted to get an insight into the fixed cost related to the maintenance actions. The standard revision of the vacuum compressor pump is €1464. To be able to service the asset, it has to be bought to the Facta workshop. The machine will be detached and transported, this will take two-person one day of work, with an hourly rate of €78 per person. The transport cost is €0.90 per km. The machine also has to be replaced after the maintenance, so the costs are multiplied by two. Resulting in a cost of €2547,48 for extracting and placing. The overall fixed maintenance cost will result in €4011.48.

Besides the fixed cost, the variable cost might play a part. The variable cost is related to the stage of the bearing damage. The stage of the bearing damage could result in secondary damage to other parts of the asset. BUSCH estimates an additional cost of 0 to 2000 euro depending on the damage. The application of the variable cost is graphically presented in figure 5.12. The variable cost starts to increase from halfway through the orange section when the damage becomes noticeable. It is assumed that this is the point when secondary damage could start to appear.

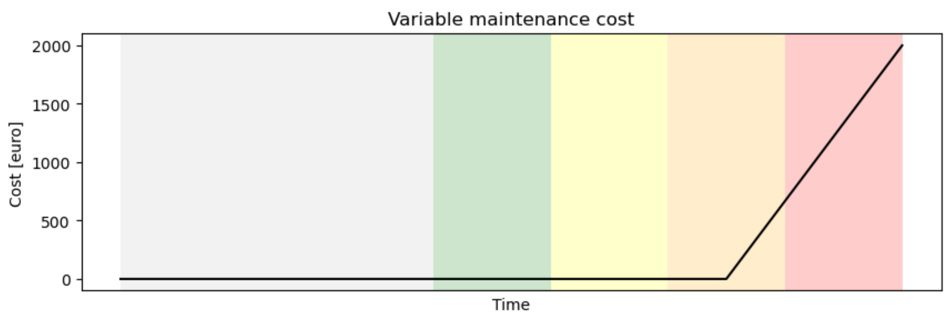



Figure 5.12: Variable maintenance cost

Besides the variable and fixed costs also the cost of buying the bearings is taken into account. As already discussed, in the vacuum compressor pumps two different types of bearings are used. Bearing 1: 3309 C3 with a cost of €122.05 and Bearing 2: SKF NU 208 ECP C3 with cost €47.74. Depending on how the data is analysed, all the bearings must be ordered, or specific bearings can be ordered. The final aspect is the express cost, €150. The express cost is added when required depending on the way the maintenance actions are planned.

**Downtime cost**

As already presented, only the unplanned downtime will be taken into account. To determine the hours downtime, $\#HourDT$, formula 5.12 is used.

$$\#HourDT = (Tdetection - EoL) + PlanningTimeExpress. \quad (5.12)$$

The hours' downtime is related to the life left in the asset at detection and the minimum time required to plan the maintenance actions, the express planning time. In the case of unexpected failure, the life left in the asset will be zero. The hours' downtime will be all the time required to plan maintenance.
The number of hours is multiplied by the cost of downtime. In the case of Duyvis, this is related to the loss of production and is €130 per hour.

**PdM program cost**
As already presented the PdM program cost is a function of different aspects. Below an overview of the cost related to the different PdM programs is presented. An broader overview of the built up of the cost related to the different PdM programs is presented in appendix E. In the table, the cost related to

| | PdM program | | | | |
|---|---|---|---|---|---|
| **Cost aspect** | 1 | 2 | 3 | 4 | 5 |
| $CAPEX_{PdM}$ | €0 | €28 | €1355.5 | €931.05 | €940.65 |
| $C_{MaintenancePdM}$* | €0 | €0 | €0 | €66.6 | €66.6 |
| $C_{Inspections}$ | €40 | €0 | €0 | €0 | €0 |
| $C_{Analysis}$ | €0 | €53 | €53 | €53 | €53 |

* Maintenance cost related to the PdM program over 4 years

Table 5.4: Cost input PdM programs

the inspections is zero for all the new programs. The inspection cost is zero when the data is collected using an online monitoring tool or when the inspection is performed by in-house staff. Currently, the inspections are performed by Facta, resulting in costs for the inspections. When in-house mechanics perform the inspections, the cost will be zero. The activities the mechanics do will change. A side node that is important to consider is that there is no cost related to performing the inspections in-house, but it requires time. Due to this, the number of inspections should be kept low.
When the inspections are done by Facta, the cost for analysing the data is incorporated. With the new programs, the data will initially be analysed in-house by Duyvis. However, when there is an alarm, the data will be analysed by experts at Facta resulting in analysis cost.

**Overview cost input**
The table below presents an overview of the cost related input.

| Cost Aspect | Value |
|---|---|
| $C_{Fixed}$ | €3400 |
| $C_{Variable}$ | €0 to €2000 |
| $C_{Bearing1}$ | €122.05 |
| $C_{Bearing2}$ | €47.74 |
| $C_{Express}$ | €150 |
| $C_{HourDT}$ | €130 |
| $CAPEX_{PdM}$ | Related to PdM program. Table 5.4 |
| $OPEX_{PdM}$ | Related to PdM program. Table 5.4 |

Table 5.5: Cost input

### 5.5.4. Output

As presented in figure 5.10 the output is related to the KPIs of the simulation cost model. The simulation cost model is used to analyse the cost-effectiveness of PdM programs. The focus will be on two KPIs, the overall cost and the reliability.
The overall cost will be the output of the cost model and is presented as a total cost over 4 years. However, it will also be represented as an average cost per year. Taking the different repetitions into account.

The reliability, KPI 2, is related to the number of unexpected breakdowns. Unexpected breakdowns occur when damage is not detected in time, and the asset reaches its EoL. Besides the number of unexpected breakdowns, the following two aspects will also be provided as output. The time to plan the maintenance actions and the type of maintenance planning used. Both aspects will be used when the number of unexpected breakdowns is similar for multiple programs. The number of unexpected breakdowns and maintenance actions will be presented as a percentage. The percentage indicates how often the option occurred over the 500 repetitions of 4 years. A high percentage indicates a high chance it will occur.

The final output aspects are the requirements. Throughout the research, it became clear that some aspects might influence the cost-effectiveness. The simulation cost model's output will give insight into the effect of these influences, which result in requirements for applying or analysing the PdM programs.

## 5.6. Assumptions

The simulation model will be used to analyse the different PdM programs. Some assumptions have been made.

The first assumption is that the maintenance actions will result in an as good as new situation. In practice, it could be possible that only repair actions are taken to extend the asset's lifetime. Such as cleaning the asset or lubricating the asset. Detecting in an early stage will give the possibility to assess if repair activities could be possible. The repair option is not taken into account in this research

The second assumption, the data is first analysed in-house by in-house staff. If there is an alarm generated and it is noticeable that something is wrong, the experts at Facta will analyse the data resulting in extra costs. This approach is only possible if the staff is willing to take the time to analyse the data and get familiar with the practice. In the model, the cost related to the analysis done by Duyvis personnel will be 0. The staff is already under contract, only their activities change.

The third assumption is related to false alarms. In this simulation model, it is assumed that the data will never generate a false alarm. When Facta is asked to analyse the data, there will always be damage. Resulting in a piece of advice on the maintenance planning.

Also, the damage will always be detected by the PdM program. Assumption 4 is that the PdM program is 100% accurate. In practice, this might not be the case. The accuracy of a PdM program is impacted by many different aspects, such as mounting position, application accuracy, the environment and the asset. The accuracy is assumed 100% because it could be said that the aspects impacting the accuracy of a PdM program will be the same for all the different options. They will all be applied to the same asset on the same location, applied by the same person.

The fifth assumption is that the failure is always the result of damage to the bearings in the pump. In practice, it could also occur that the bearings inside the motor start to fail. According to Martin Franssen from BUSCH this is less likely. Due to the higher tolerance of the bearings inside the motor and higher load on the bearings inside the pump. Also, the cost and planning time required for a failure occurring inside the pump will be higher. So if the PdM program is cost-effective for a failing pump, it is also expected that the program will be cost-effective for failures related to the motor. This difference will only influence the cost but not the ability of the PdM program to detect failures.

One of the aspects that is proven to be challenging to determine is the failure distribution. The sixth assumption. It is assumed that the probability a pump fails within the 4 years is 100%. Scenarios where this is not the case will also be analysed. But unless stated otherwise, the asset will fail, at least once, within the simulation period.

The final assumption is related to the inspections. It is assumed that when the inspections are done, the asset is always on. The asset has a discontinuous operating profile which does influence the data gathered of the online applications. However, it is assumed that the inspections are planned so that the asset will be ON.

## 5.7. Application programs

In this section, an overview of the application for the different PdM programs is presented. This is done by presenting the flow diagram used and the specific input required.

### PdM program 1: current situation

The flow scheme presented in section 5.3.3. in figure 5.8 is used to simulate the current situation, PdM program 1. The current situation is used in the simulation to determine the base case and the effect of the different PdM options on the current situation. Information used to simulate this PdM program is presented in table 5.6.

| Sample freq | % ON | Detect-ability | CAnalysis | CInsp | CMaintPdM | CAPEX |
|---|---|---|---|---|---|---|
| 3 or 4 Months | 100% | 1,2,3,4 | €0 | €40 | €0 | €0 |

Table 5.6: Information simulation PdM program 1

### PdM program 2

The second program, the Quick Collect, uses the flow diagram presented in figure 5.13 and the information presented in table 5.7.

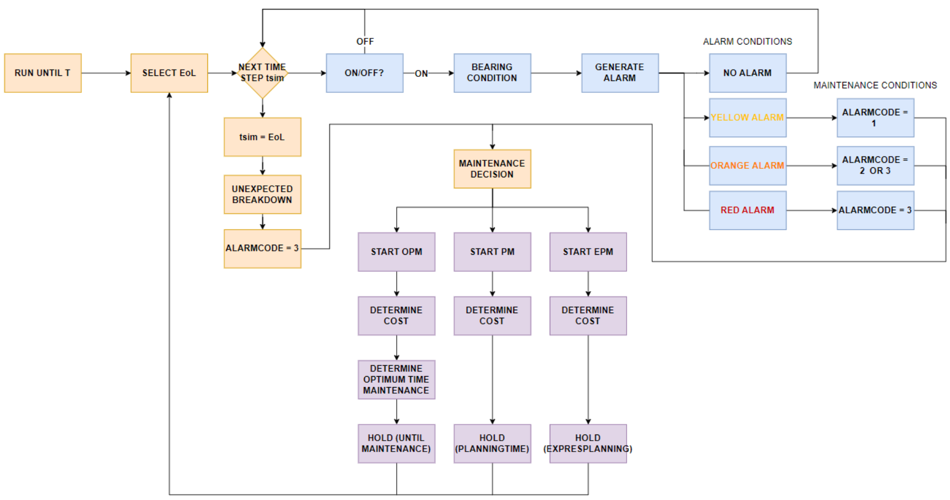



Figure 5.13: Flow diagram PdM 2 and 3

| Sample freq | % ON | Detect-ability | CAnalysis | CInsp | CMaintPdM | CAPEX |
|---|---|---|---|---|---|---|
| 2 Month | 100% | 2,3,4 | €0 | €53 | €0 | €28 |

Table 5.7: Information simulation PdM program 2

**PdM program 3**

To simulate PdM program 3, IMx1, the same flow diagram is used as for PdM program 2, figure 5.13. Both PdM programs are able to detect damage at stage 2,3 and 4. The main difference between the two is the CAPEX and the sample frequency. The information used to analyse PdM program 3 is presented in table 5.8.

| Sample freq | % ON | Detect-ability | CAnalysis | CInsp | CMaintPdM | CAPEX |
|---|---|---|---|---|---|---|
| 3 hour | 27% | 2,3,4 | €0 | €53 | €0 | €1307.5 |

Table 5.8: Information simulation PdM program 3

**PdM program 4**

PdM program 4, Banner, is only able to detect damage at stage 3 or 4. However it has a much higher sample frequency. Due to this the flow diagram is slightly different. There is only the option for a 'Orange' or 'Red' alarm. These alarms are only able to generate alarm code 2 or 3 resulting in PM or EPM. Due to this the OPM option is removed from the diagram. The flow diagram used is presented in figure 5.14. The information used is presented in table 5.9.

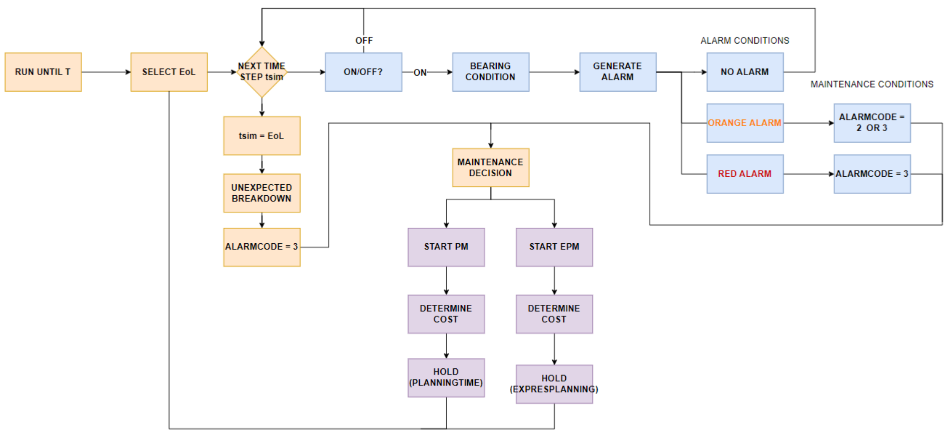



Figure 5.14: Flow diagram PdM 4

| Sample freq | % ON | Detect-ability | CAnalysis | CInsp | CMaintPdM | CAPEX |
|---|---|---|---|---|---|---|
| 5 min | 27% | 3,4 | €0 | €53 | €66.6 | €931.05 |

Table 5.9: Information simulation PdM program 4

**PdM program 5**

The final PdM program is a combination of program 2 and 4, a combination of the Quick Collect (QC) and the Banner application. Program 5 will use the information of both programs, presented in table 5.10. Depending on the time, related to the sample frequency, either the QC or the Banner system is used to gather the data. If the QC is used to gather the data, damage can be detected in stage 2, 3 or 4. If the data is collected with the Banner application damage is only detected at a stage 3 or 4. The flow diagram used to simulate this program is presented in figure 5.15.

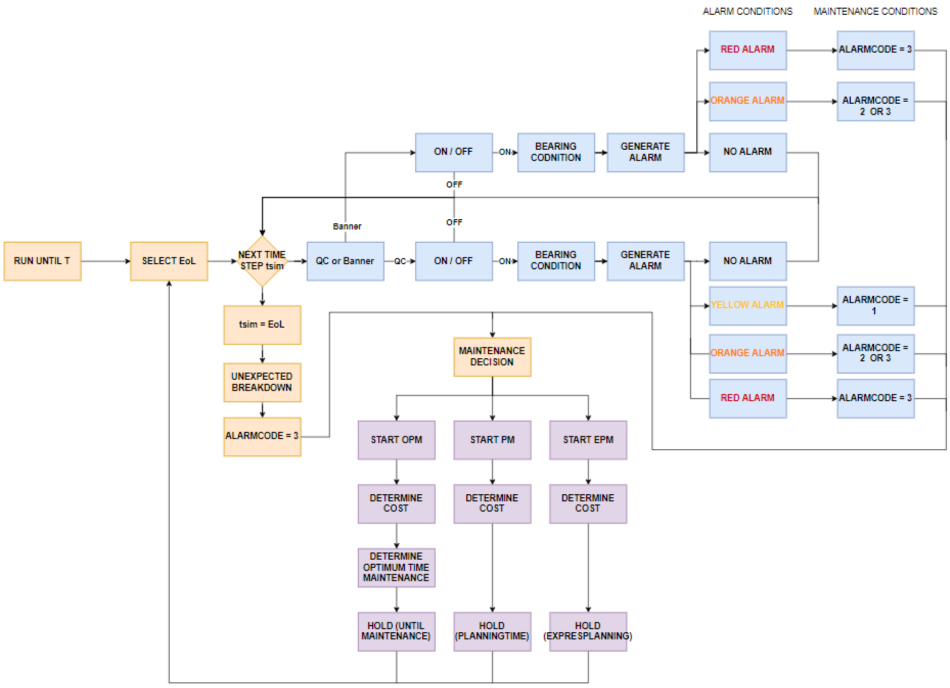



Figure 5.15: Flow diagram PdM 5

| | Sample freq | % ON | Detect-ability | CAnalysis | CInsp | CMaintPdM | CAPEX |
|---|---|---|---|---|---|---|---|
| **QC** | 4 Month | 100% | 2,3,4 | €0 | €53 | €0 | €28 |
| **Banner** | 5 min | 27% | 3,4 | €0 | €53 | €66.6 | €931.05 |

Table 5.10: Information simulation PdM program 5

It is important to take into account that the CAPEX and the maintenance cost of the PdM program will always be the sum of the two programs. Even when only the data is used from one of the two applications.

## 5.8. Conclusion

The cost-effectiveness of PdM programs will be analysed by simulating the effect of the PdM programs on the overall cost and reliability. This is done by using a DES model to represent the program's application over 4 years. The DES model will select an EoL of a failure distribution and determine the assets condition based on alarm conditions. The output of the DES model will partially be used to give insight into the reliability (KPI 1) and partially be used as input for the cost model to determine the overall cost (KPI 2). The combination of the DES and cost model results in a simulation cost model.

So, the is the answer to sub-question 4, *how is the cost-effectiveness of the PdM programs analysed?* is in one line. Using the simulation cost model.

# 6

# Implementation and Results

This chapter presents the results of using the simulation cost model to analyse the cost-effectiveness of the proposed PdM programs. Before generating the results, the model is verified. Followed by a sensitivity analysis to assess the impact of some of the parameters and analysing the robustness of the model. After the verification and sensitivity analysis, a test plan will be presented used to structure the research. Followed by the results and a discussion and limitations.
The information provided in this chapter will give insight into the PdM programs' cost-effectiveness, which can be used to advise on an application for Duyvis.

## 6.1. Verification

Verification is a process that is used to determine if the "model is right". This means assessing if the model is built up in the correct way and is working as desired. The verification of the simulation cost model is an ongoing process. Throughout the development of the model, different components have been checked and verified. The overall verification of the model will be done with a simplified model. The input will later be adjusted to analyse the different PdM programs. The data used in the simplified model is in days and not in minutes to make it easier to trace the activities. A situation where the inspections are performed every 3 months is used, and the program can detect all 4 stages of bearing damage.

In general, the first step of verification is to make sure the model is error-free [31]. When the errors are removed, the simulation model can be used. The next step is to check if the model works as expected, this can be done by static or dynamic testing [31]. The simulation cost model is verified using dynamic testing. Dynamic testing can be done using different techniques. The first technique that is used is tracing. Tracing is a method of following the output of the model. The model will be used, and the different steps taken will be printed. This information is used to assess if the elements of the model behave as expected [29]. Aspects that seem off during the tracing are further analysed and have been adjusted. This is repeated until the trace of the model is as expected.

Besides tracing, another technique will be used. This is the investigation of input-output relations [31]. The input-output relations are assessed by altering the input variables to check if the output changes as expected. 5 tests have been done specifically for the verification. The first four test consists of altering the input to check if the output changes as expected. The fifth test is a check that uses a numerical example to check the output. In table 6.1 the results of the tests are presented, appendix F contains information used to fill in this table.
The test all present results that are as expected. Results from the tracing and input-output relations show that the model works as expected and is verified.

Usually, the model would also be validated. However, in this research, this is not yet possible. Validation requires the ability to check if the model is representing the real-world problem. To do this, data on the situation should be available or similar models that can be used to compare. In this case, both options are not possible, and the advice is to do further research on the validation of the model.

| Test | Description | Expectation | Result | PASS? |
|---|---|---|---|---|
| Test 1 | Switching the alarm conditions for green and yellow alarms | The number of yellow and green alarms will switch | #Green alarms = #Yellow alarms | PASS |
| Test 2 | Doubling the fixed cost for maintenance actions | Increase in overall cost | First: €2492 After: €4325 | PASS |
| Test 3 | Reducing the percentage the asset is ON from 100% to 50% | Higher number No Data detected | From 0 No data counts to 400 No Data counts | PASS |
| Test 4 | Only using alarm code 2 | Only PM and EPM in the case of an UBD | First: 22 PM after: 54 PM | PASS |
| Test 5 | Checking the cost of Downtime using | Cost Down Time = €6240 in case of UBD | EoL = 353, UBD = 1, Cdt = €6240 | PASS |

Table 6.1: Verification results input-output relation

## 6.2. Sensitivity analysis

Besides the verification also a sensitivity analysis is done. A sensitivity analysis will assess the impact of certain parameters on the overall results. It gives insight into the robustness of the model. The sensitivity analysis results are used to determine the critically of the different parameters, which should be further investigated or taken into account when making a decision. The sensitivity analysis is done for the parameters related to the general input. These parameters are the same for all the different programs. They will be analysed for a higher and a lower value than the current situation. The exact number is related to the uncertainty of the parameter and assesses what could be logical values for the situation. The parameters and values assessed are presented in table G.1.

| # | Parameter | Base case | Lower value | Higher value |
|---|---|---|---|---|
| 1 | Planning time | 14 days | 3 days | 21 days |
| 2 | Express planning time | 2 days | 0 days | 7 days |
| 3 | Simulation time | 4 years | 2 years | 8 years |
| 4 | Starting point variable cost | 3 weeks | 1 week | 5 months |
| 5 | Number of data points required (X) | 10 | 1 | 25 |
| 6 | Likeliness infant mortality | 0.05 | 0.01 | 0.15 |
| 7 | Likeliness usage failure | 0.6 | 0.45 | 0.75 |
| 8 | Likeliness wear out | 0.35 | 0.2 | 0.5 |

Table 6.2: Parameters for the sensitivity analysis

The results for the sensitivity analysis on the overall cost and the reliability give similar results. In figure 6.1 results of the sensitivity analysis on the overall cost are presented. In this graph, the effect of the different parameters related to the PdM programs is presented. The orange bars represent the lower

values, and the blue bars represent the higher values. The base case is 0, and the bars indicate how much the overall cost differs from the base case in percentage.
The results related to the reliability have been added to appendix G

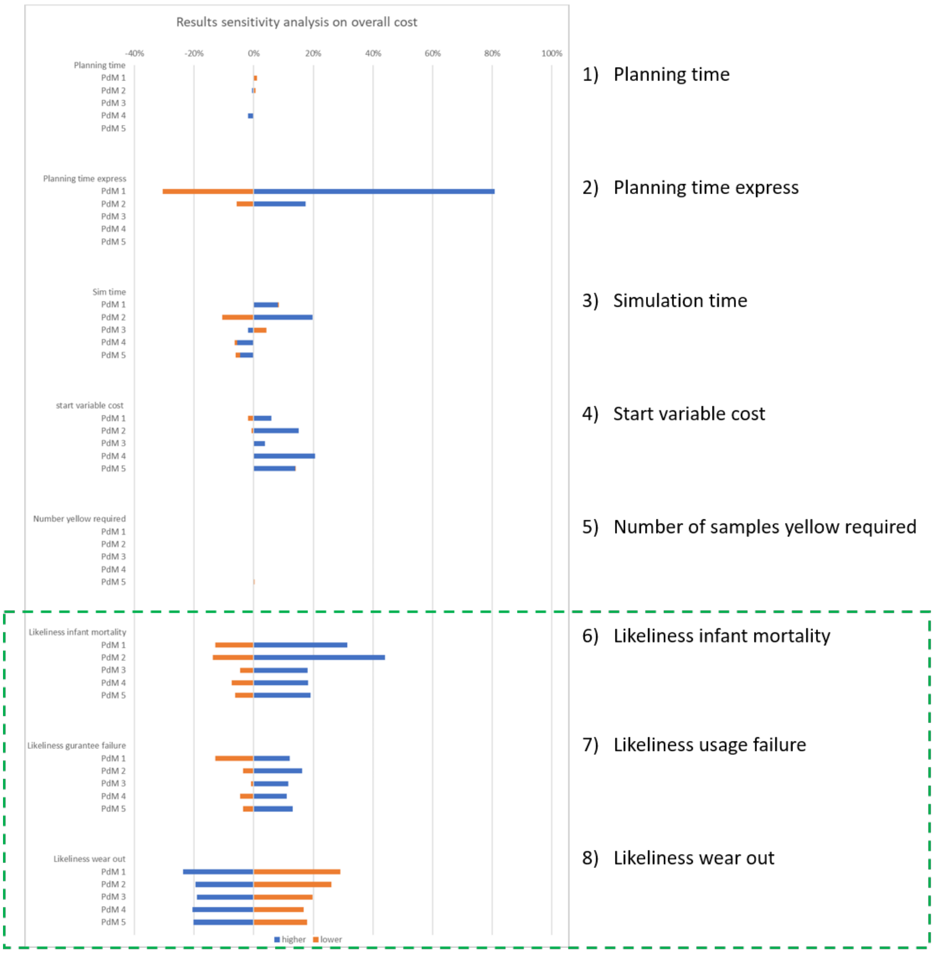



Figure 6.1: Results sensitivity analysis

The results show that the parameters that cause the highest fluctuation in the results are the parameters linked to the failure distribution, the likeliness of infant mortality, usage failure, or wear out, presented in the green box. All the programs are influenced by the change in these parameters. A side note is that due to the influence on all the programs, it could be that the ratio between the options is similar. Further research is conducted to gain insight into the effect of different failure distributions on the outcome and assess if this influences the ratio between the programs.

Besides the effect of the failure distribution, there is also a high effect noticeable for programs 1 and 2 when the express planning time is adjusted. It is expected that the change is only noticeable in these two programs because they are discontinuous programs and probably use express planning more often. Another parameter that influences the results is the variable cost. The effect is as expected. When the start moment of the variable cost is at an earlier moment in time, so higher. The overall cost will increase, the likeliness the variable cost is added is increased.
The conclusion of the sensitivity analysis is that in general, the parameters act as expected, and only the aspects related to the overall failure distribution require more attention.

## 6.3. Test Plan

As already presented, the simulation cost model is used to gain insight into the cost-effectiveness of a selection of PdM programs for the vacuum compressor pumps at Duyvis. In figure 6.2 an overview of the relation used to analyse the programs is presented.

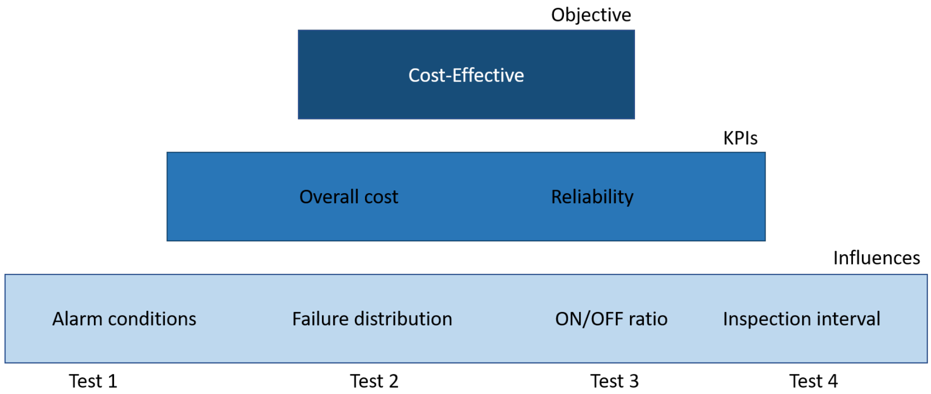



Figure 6.2: schematic overview test plan

To analyse the cost-effectiveness of PdM programs, two KPIs are used, the overall cost and the reliability. The overall cost is a function of the three cost categories: maintenance, unplanned downtime, and the PdM program. The reliability is related to the number of unexpected breakdowns. If the number of unexpected breakdowns is the same for multiple programs, the use will be made of the time available for planning and the type of maintenance planning used: EPM, PM, or OPM.

Throughout the research, it became clear that 4 aspects could influence the results of the simulation cost model. These influences are the alarm conditions, failure distribution, ON/OFF ratio and the inspection interval. 4 tests will be conducted to analyse the effect of the 4 different influences on the outcome of the simulation cost model.

In general, the tests will use the following information unless stated otherwise. The simulation time is 4 years, and there will be 500 repetitions. The failure distribution will be based on the information provided by Atlas Copco, this means the asset will at least fail once every simulation run. The input required is based on the information provided in section 5.5.1.

Per test, the following information is presented.

- General information: Why and how is the influence analysed
- Results: The overall cost and/or the reliability related to the different options analysed in the tests
- Conclusion: Using the results what can be concluded over the effect of the influence on the outcome of the model.

The results give insight into the effect of the influences on the overall cost and reliability. The overall cost will be presented as a total cost over the 4 years or an average per year related to the 500 repetitions. The reliability will be presented as a percentage of unexpected breakdowns and the type of maintenance planning used over the 500 repetitions. Also, the average time to plan the maintenance actions will be presented, the average time available between the detection and the selected EoL.

Besides the 4 tests also a ”worst-case” scenario will be analysed. The scenarios will be built up of the influences and the information gathered in the tests.
In the next section, the results of the different tests and the ”worst-case” scenario will be presented.

## 6.4. Results cost-effectiveness analysis

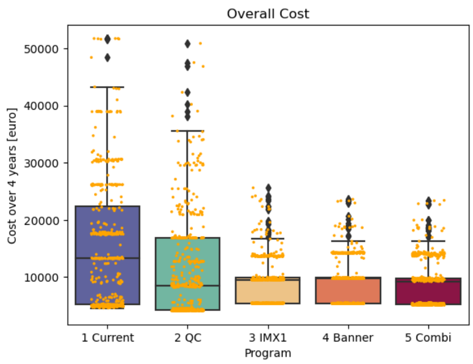
In this section, the result of the 4 tests and the ”worst-case” scenario will be presented. The results of test 1 will include an explanation of how the different KPIs are presented and visualised. Similar figures will be used in the other tests to present the results.

### 6.4.1. Test 1: Alarm conditions

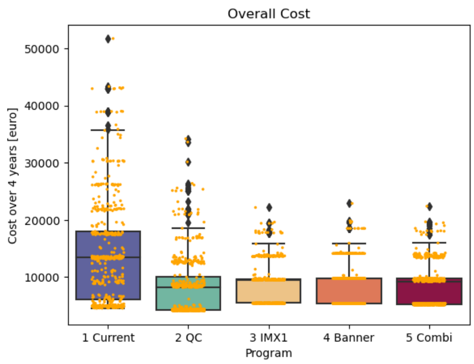
The first test focuses on the influence of the alarm conditions on the outcome of the model. The alarm conditions are an important aspect of the simulation cost model. They are related to the different stages of bearing damage. The alarm conditions can be based on the information presented in the literature or can be based on information used in practice, presented in section 5.3.3. The effect of these two options on the overall cost and reliability is analysed by running the simulation using both alarm conditions. The results are presented below.

**Overall Cost test 1**

The overall cost is presented as a box-plot per PdM program, figure 6.3a and 6.3b. The box-plot presents the average and spreading of the overall cost over 4 years. The yellow marks in the figure are the overall cost over 4 years related to the repetitions. The simulation is done for 500 repetitions resulting in 500 yellow marks. Besides the figures also a table is presented, table 6.3. The table presents the percentile reduction in cost compared to the current situation, program 1.




(a) Overall cost literature




(b) Overall cost practice

Figure 6.3: Overall cost related to the alarm conditions

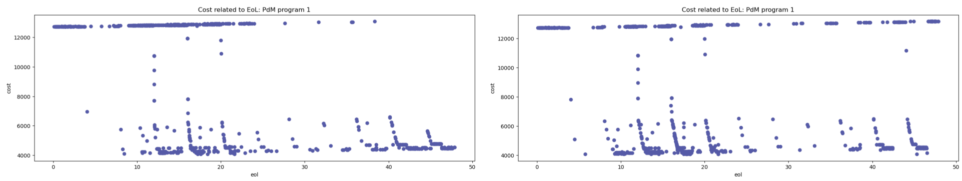
| Based on | Program 1 | Program 2 | Program 3 | Program 4 | Program 5 |
|---|---|---|---|---|---|
| Literature | 0 | -29% | -43% | -44% | -45% |
| Practice | 0 | -43% | -40% | -40% | -41% |

Table 6.3: Difference in average cost per year related to the current situation

Figure 6.3a presents the overall cost related literature-based alarm conditions, while figure 6.3b is related to the practice-based alarm conditions. One program shows a significant difference in overall cost related to the different alarm condition options, program 2. The spreading of the cost and the average cost is lower when the alarm conditions are based on practice. This is also visible in the data presented in table 6.3. The reduction is only 29% using the literature-based alarm conditions and is 43% for the practice option. For the other programs the effect of the alarm conditions on the overall cost is minimal.

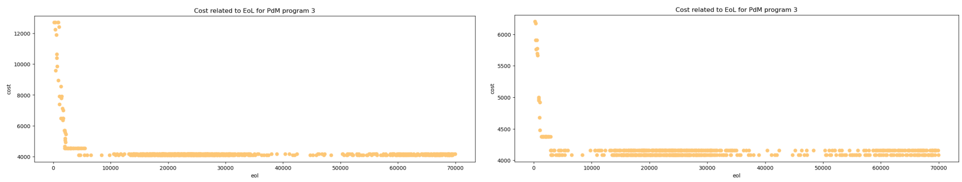
**Cost per EoL**

Besides presenting the overall cost, it is important to know that the different programs have a certain cost related to a specific end-of-lifetime (EoL). The overall cost is related to how often a certain EoL is selected. The selection of the EoL is related to the failure distributions used. In figure 6.4 the cost per EoL for program 1 is presented. Figure 6.5 presents the cost per EoL for program 3. In both cases, the results based on literature and practice alarm conditions are presented. In these figures, it becomes even more visible that the different alarm conditions influence the outcome. The same trend is generally seen, but for the short EoL time, the cost is higher for the literature-based alarm conditions. This can be explained by the fact that literature-based alarm conditions are related to a percentage of the EoL. This means that if the EoL is early, the damage evolves very quickly, resulting in late detection or no detection. Late or no detection will increase the overall cost due to the effect of secondary damage, express cost and the cost related to unplanned downtime.




(a) Cost per EoL program 1 (literature) (b) Cost per EoL program 1 (Practice)

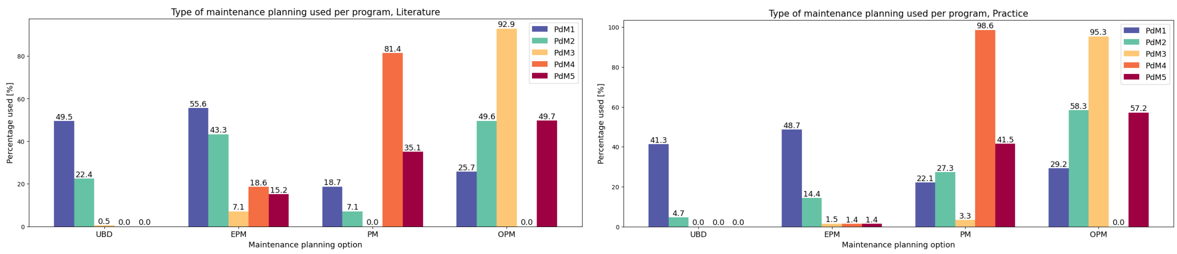
Figure 6.4: Cost related to an EoL for program 1




(a) Cost per EoL program 1 (literature) (b) Cost per EoL program 1 (Practice)

Figure 6.5: Cost related to an EoL for program 3

**Reliability test 1**
the reliability is visualized using a bar-plot, presented in figure 6.6a and 6.6b. The bar plot presents the percentage a certain maintenance planning or an unexpected breakdown has occurred. The percentages are related to all the maintenance actions and unexpected breakdowns over the 500 receptions. The time available for planning is presented in table 6.4. The time available for planning the maintenance actions is the time between detection of the damage and the selected EoL. The average time to plan is in weeks.




(a) Maintenance type literature (b) Maintenance type practice

Figure 6.6: Maintenance planning used and unexpected breakdowns related to the alarm conditions

| Based on | Program 1 | Program 2 | Program 3 | Program 4 | Program 5 |
|---|---|---|---|---|---|
| *Literature* | 1.9 | 5.8 | 8.0 | 4.4 | 5.9 |
| *Practice* | 2.0 | 6.2 | 8.0 | 5.4 | 6.9 |

* Time to plan in weeks

Table 6.4: Time available to plan the maintenance actions in weeks

The difference between the alarm conditions is better visible assessing the reliability. The bar-plot shows that the percentage of unexpected breakdowns and express planned maintenance is lower

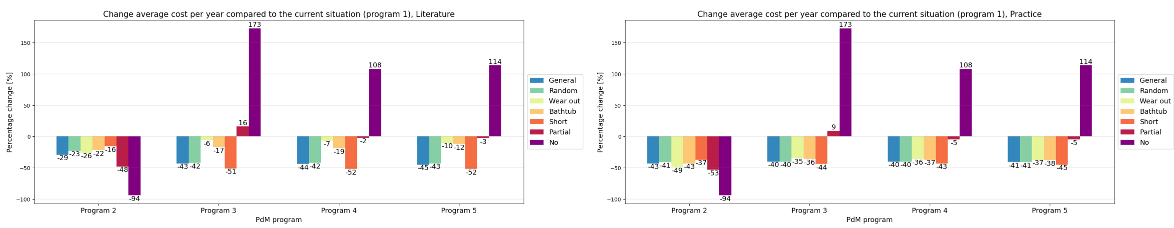
when the alarm conditions are based on practice compared to the results of the literature-based alarm conditions.
The reduction in these aspects can also explain the difference in the overall cost. The main difference in the overall cost is visible for program 2. Program 2 shows the largest difference in reliability. The difference in the number of unexpected breakdowns is 17.7%. An unexpected breakdown has the highest effect on the overall cost.
The change is most visible for program 2, but it is occurring in all the different programs. So is the chance that an unexpected breakdown will occur with program 3 gone from 0.5% literature-based to 0% practice-based. It is only a small difference, but it is important to keep in mind. Unexpected breakdowns are an important aspect of reliability and should be as low as possible. In general, the reliability related to the programs will increase when the alarm conditions are based on practice.

**Conclusion test 1**
Using the information provided, it can be concluded that the two different alarm conditions influence the model's overall outcome. The main difference between the alarm conditions is that all the programs are more reliable when the alarm conditions are based on practice. There are less unexpected breakdowns and EPM used. Due to the difference between the options and the inability to select the most suited one, both options will be used to assess the other influences in the remaining tests.

## 6.4.2. Test 2: Distributions

The second test focuses on the influence with the highest uncertainty, the failure distribution. The failure distribution is used to select an EoL with a certain probability. The exact failure distribution is uncertain, so this test is done to assess the impact of the failure distribution on the outcome. 7 different failure distributions, presented in section 5.5.1, will be analysed. The failure distributions are 1)General, 2)Random, 3)Wear-out, 4)Bathtub, 5)Short, 6)Partially, and 7)No failure.

**Overall cost test 2**
The simulation is used to analyse the overall cost of the PdM programs for the different failure distributions. The overall cost is related to the number of failures. The number of failures, and thus maintenance actions conducted, per program are related to the selected EoL. When the probability of selecting an early EoL increases, the number of maintenance actions will, in general, also increase. Shorter EoL leaves more time to have another failure within the complete simulation time. The failure distribution affects the probability that a certain EoL is selected. Due to this reason, the different failure distributions can result in very different overall costs. However, this does not directly influence the decision of a program. It is important to assess the ratio between the programs using the same distribution. In table F.1 and figure 6.7 the difference in overall cost related to the current situation, program 1 is presented. The current situation will be simulated using the same failure distribution as the programs compared to it. The difference is presented as a percentage. A negative value will indicate that the cost will decrease using the new program.




(a) Difference in cost, literature

(b) Difference in cost, practice

Figure 6.7: Difference in cost related to program 1 for the different failure distributions and programs.

The difference related to the failure distributions is most visible when the literature-based alarm conditions are used. Due to the higher difference in cost related to a certain EoL for the literature based alarm conditions.

| Program | General | Random | Wear out | Bathtub | Short | Partially | No failure |
|---|---|---|---|---|---|---|---|
| *Literature-based alarm conditions* | | | | | | | |
| PdM 2 | -29% | -23% | -26% | -22% | -26% | -48% | -94% |
| PdM 3 | -43% | -42% | -6% | -17% | -51% | 16% | 173% |
| PdM 4 | -44% | -42% | -7% | -19% | -52% | -2% | 108% |
| PdM 5 | -45% | -43% | -10% | -21% | -52% | -3% | 114% |
| *Practice-based alarm conditions* | | | | | | | |
| **Program** | **General** | **Random** | **Wear out** | **Bathtub** | **Short** | **Partially** | **No failure** |
| PdM 2 | -43% | -41% | -49% | -43% | -37% | -53% | -94% |
| PdM 3 | -40% | -40% | -35% | -36% | -44% | 9% | 173% |
| PdM 4 | -40% | -40% | -36% | -37% | -43% | -5% | 108% |
| PdM 5 | -41% | -41% | -37% | -38% | -45% | -5% | 114% |

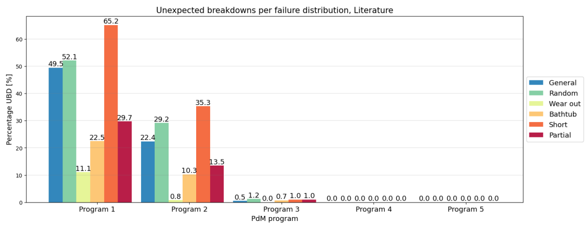
Table 6.5: Difference in cost compared to the current situation for the different failure distributions

However in both cases there is a difference noticeable between the first 5 programs and the last 2 programs. The first 5 programs have one main aspect in common. They all have a 100% probability the asset will fail at least once during the simulation period. All the programs will in reduce the cost.

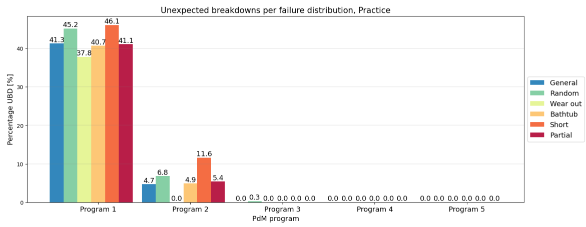
The last 2 failure distributions do not use this assumption. Due to the possibility the asset will not fail the influence of the PdM program cost increases. This is best explained using failure distribution 7, no failure. In this case the asset will not fail during the simulation time, the overall cost will in this case only be related to the cost for the PdM program cost. The high investment cost related to on-line programs will result in a higher overall cost than the current situation, marked in red in table 6.7. Program 2 on the other hand will be the best option in a situation where it is uncertain the asset will fail, if the decision was solely based on the overall cost. This is due to the low investment cost and no operational cost when there is no failure.

In general it could be said that altering the program will reduce the overall cost. As long as there is a certainty on a failure occurring during the application period. So not only cost but also the benefits are incorporated in the cost.

**Reliability test 2**
the effect of the failure distributions on the reliability is analysed using the chance of an unexpected breakdowns. This is analysed by determining how much percent of the total maintenance actions are related to an unexpected breakdown. The total maintenance actions are all the maintenance actions over the 500 repetitions of 4 years. The result of the test is presented in table6.6 and figure 6.8.




(a) Chance of unexpected breakdown, literature




(b) Chance of unexpected breakdown, practice

Figure 6.8: Difference in cost related to program 1 for the different failure distributions and programs.

The red marked values in table 6.6 indicate the possibility of unexpected breakdowns. Again the effect of the alarm conditions is noticeable. However, there can be a general pattern detected. In all cases, PdM program 1 has the highest percentage of unexpected failures. Followed by program 2, and program 3 has, in some cases. Programs 4 and 5 are the most reliable in all the situations, for the different failure distributions and alarm conditions.

| *Literature-based alarm conditions* | | | | | | |
|---|---|---|---|---|---|---|
| **Program** | **General** | **Random** | **Wear out** | **Bathtub** | **Short** | **Partially** |
| PdM 1 | 49.5% | 52.1% | 11.1% | 22.5% | 65.2% | 29.7% |
| PdM 2 | 22.4% | 29.2% | 0.8% | 10.3% | 35.3% | 13.5% |
| PdM 3 | 0.5% | 1.2% | 0.0% | 0.7% | 1.0% | 1.0% |
| PdM 4 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| PdM 5 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| *Practice-based alarm conditions* | | | | | | |
| **Program** | **General** | **Random** | **Wear out** | **Bathtub** | **Short** | **Partially** |
| PdM 1 | 41.3% | 45.2% | 37.8% | 40.7% | 46.1% | 41.1% |
| PdM 2 | 4.7% | 6.8% | 0.0% | 4.9% | 11.6% | 5.4% |
| PdM 3 | 0.0% | 0.3% | 0.0% | 0.0% | 0.0% | 0.0% |
| PdM 4 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| PdM 5 | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |

Table 6.6: Occurrence unexpected breakdown in percentage.

Using wear-out as failure distribution will, in general, result in the highest level of reliability. With the wear-out distribution, the failures occur after a long period. Due to this, all the programs will have data collected before the failure occurs. An unexpected failure is now related to a moment where the failure occurs just before the next inspection.

Random and short failure distributions result in the least reliable scores. The probability that an early EoL is selected is relatively high for these options. An early EoL is, in general, more prone to result in unexpected breakdowns.

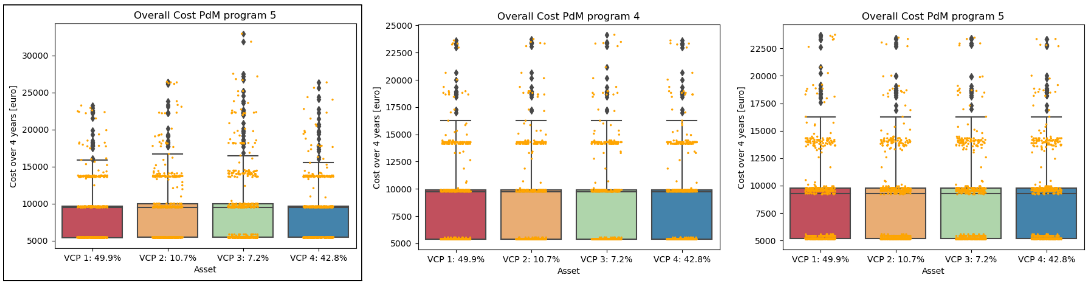
**Conclusion test 2**
Using this information, one general conclusions can be made. It is important to get a general idea of the failure distribution of the asset. The most important aspect to know is the probability the asset will fail during the program's life cycle.

### 6.4.3. Test 3: ON/OFF ratio

The chosen PdM program will be applied to 4 identical vacuum compressor pumps. The only difference between the pumps is the operating profile, which results in different ON/OFF ratios. The effect of the ON/OFF ratios on the cost-effectiveness of the PdM programs is unknown. This test, test 3, is conducted to analyse the effect of the ON/OFF ratios. Insight into this influence will make it possible to select the most cost-effective PdM program for all pumps.

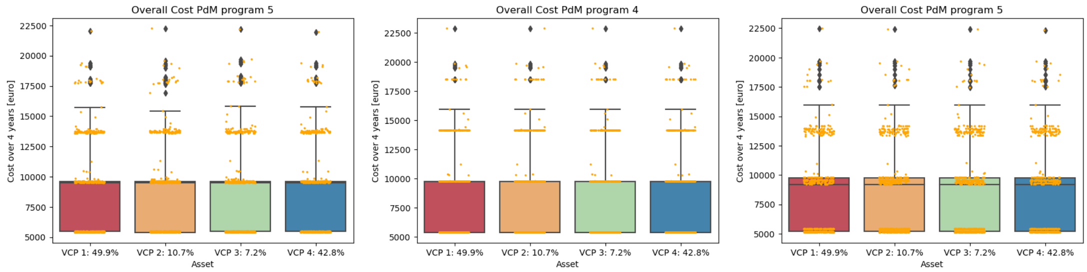
The ON/OFF ratios of the 4 pumps are presented in section 5.5.1. In the simulation model, the percentage the asset is ON is used. For the 4 pumps, these are: 49.9%, 10.7%, 7.2% and 42.8%. The effect of the ON/OFF ratios is only analysed for programs 3,4, and 5. Programs 1 and 2 are not taken into account because it is assumed that the inspections used in these programs are planned so that the asset is always ON.
The test is done using the standard failure distribution and the alarm conditions based on literature as on practice.

**Overall cost test 3**
Below the overall cost related to the 3 programs applied to the different pumps is presented in table 6.7 and in figures 6.10. The figures show no clear impact related to the ON/OFF ratios. The only difference that can be seen is related to program 3, especially when the literature-based alarm conditions are used, figure 6.9a. In this figure, the fluctuation of the cost is higher for pumps 2 and 3. In table 6.7, the average cost related to a program is presented. Here it becomes clear that only program 3 is affected by the application on the different pumps. The other two programs are not influenced.




(a) Overall cost PdM program 3 (b) Overall cost PdM program 4 (c) Overall cost PdM program 5

Figure 6.9: Overall cost per asset per PdM program related to the ON/OFF ratios, Literature based alarm conditions




(a) Overall cost PdM program 3 (b) Overall cost PdM program 4 (c) Overall cost PdM program 5

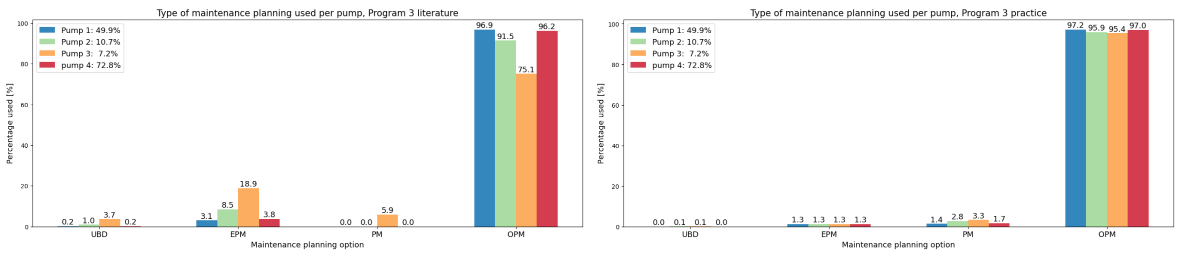
Figure 6.10: Overall cost per asset per PdM program related to the ON/OFF ratios, practice based alarm conditions

| **pump** | **PdM 3** | | **PdM 4** | | **PdM 5** | |
|---|---|---|---|---|---|---|
| | *Practice* | *Literature* | *Practice* | *Literature* | *Practice* | *Literature* |
| **1** | €2185 | €2198 | €2193 | €2202 | €2121 | €2160 |
| **2** | €2182 | €2248 | €2193 | €2203 | €2121 | €2160 |
| **3** | €2177 | €2360 | €2193 | €2203 | €2120 | €2160 |
| **4** | €2187 | €2206 | €2193 | €2202 | €2120 | €2161 |

Table 6.7: Average cost per year, ON/OFF analysis

### Reliability test 3

Besides the overall cost also the reliability is assessed. Similar to the overall cost, only the reliability of program 3 is affected by the ON/OFF ratios. In figure 6.11, the percentage a certain maintenance type is used is presented. Only the results of the application of program 3 on the different pumps are presented. The results of the reliability analysis of programs 4 and 5 related to this test are presented in appendix H.3.




(a) Maintenance planning (literature) (b) Maintenance planning (practice)

Figure 6.11: The effect of ON/OFF ratios on the maintenance planning used PdM program 3

| Based on | Pump 1 | Pump 2 | Pump 3 | Pump 4 |
|---|---|---|---|---|
| *Literature* | 8.5 | 7.2 | 6.3 | 8.5 |
| *Practice* | 10.3 | 9.0 | 8.0 | 10.2 |

Table 6.8: Time available to plan the maintenance actions in weeks for program 3

The figures show that the percentage a certain maintenance type is used is affected by the different ON/OFF ratios of the asset. The number of OPM decreases for pumps 2 and 3 compared to pump 1 and 4. The effect is most noticeable when the literature-based alarm conditions are used. A similar effect is seen when looking into the time available to plan the maintenance actions, table 6.8. The cause of the difference between the pumps is explained below.

When the ON% is reduced also the reliability decreases. This effect is related to the sample frequency of the program and the amount of useful data collected. The sample frequency of online condition monitoring applications is set. Due to this, it might be the case that the program tries to collect data when the asset is OFF. This data will be unuseful for determining the assets condition. Program 3 is most influenced by this aspect because the sample frequency, every 3 hours, is relatively low compared to the sample frequency of the Banner application, every 5 minutes. The Banner application is used in programs 4 and 5. A numerical example to explain the effect of the different ON/OFF ratios on the amount of useful data is presented below.

*Numerical example: effect ON/OFF ratio on useful data*
When the data is collected over a day, 24 hours, and the asset is on for 100% of the time. The following number of useful data samples are collected. Program 3, using the IMx1, collects 7 samples, while program 4 and 5, using Banner, are able to collect 288 samples. The number of samples is determine by dividing 24 hours by the time between the samples. When the ON% is reduced to only 10%. Only 0.7 data samples will be useful when the IMX1 is used. For the Banner application, there are still 28.8 useful samples.

**Conclusion test 3**
Based on the test results, it can be concluded that only program 3 is influenced by the different ON/OFF ratios. However, the extent of the influence is highly influenced by the alarm conditions. When the alarm conditions are based on literature, the influence is more severe, the chance of an unexpected breakdown increases from 0.2 to 3.7% for pump 3. Compared to an increase from 0 to 0,1% for pump 3 when practice-based alarm conditions are used. Although the exact extent of the ON/OFF influence is unclear, it is still a factor that should be taken into account when decisions are made on the most cost-effective PdM program.

### 6.4.4. Test 4: Inspection Interval

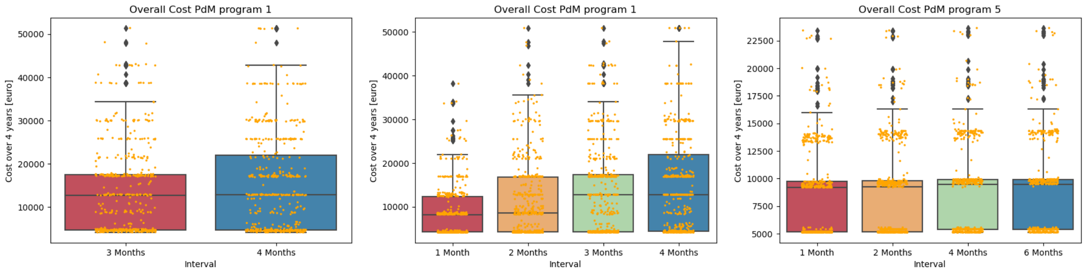
Test 4 focuses on the effect of the inspection interval on the results of the simulation cost model. Inspections are, entirely or partially, used in programs 1, 2 and 5 to collect data. The time between inspections can easily be adjusted.

Different inspection intervals will be analysed.

- Program 1: 3 and 4-month
- Program 2: 1, 2, 3, and 4-month
- Program 5: 1, 2, 4, and 6-month

**Overall cost test 4**

The overall cost related to the different inspection intervals of the PdM programs is presented. The literature-based alarm conditions are used in these figures.



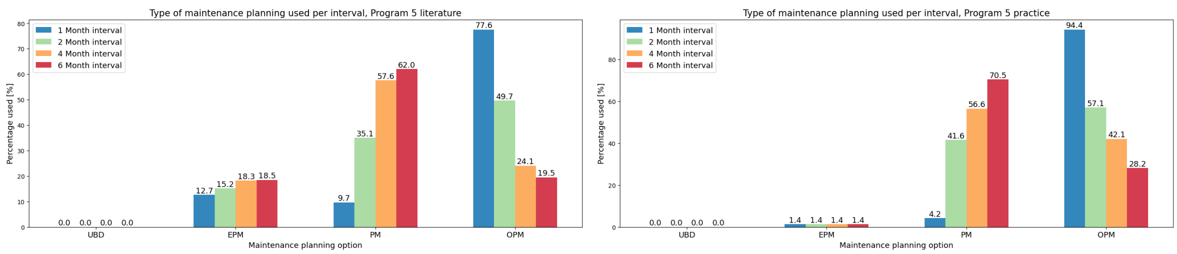

(a) Cost related to PdM 1. (b) Cost related to PdM 2. (c) Cost related to PdM 5

Figure 6.12: Overall cost related to inspection intervals (literature)

Figure 6.12a presents the overall cost related to program 1 and figure 6.12b for program 2. Both figures show similar results. The results are as expected. With the increase in time between samples, the cost will also increase. When the sample frequency decreases, the chance damage is missed increases, which will result in higher costs.
This relation between the inspection frequency and the cost is not seen in program 5, figure 6.12c. The overall cost related to program 5 is not influenced by the increase in inspection interval.

**Reliability test 4**

The reliability related to program 5 is analysed to assess if program 5 is not at all influenced by the inspection interval. In figure 6.13 the percentage a certain maintenance planning is used related to program 5 with different inspection intervals is presented. Figure 6.13a contains the results based on the literature-based alarm conditions. The practice-based alarm conditions are used in figure 6.13b. Table 6.9 contains the average time available to plan the maintenance actions in weeks.




(a) Maintenance actions related to inspection interval (literature) (b) Maintenance actions related to inspection interval (practice)

Figure 6.13: Maintenance actions for program 5 related to the inspection interval options

| Based on | 1-Month | 2-Month | 4-Month | 6-Month |
|---|---|---|---|---|
| *Literature* | 6.9 | 5.9 | 5.1 | 5.0 |
| *Practice* | 8.5 | 6.9 | 6.5 | 6.1 |

Table 6.9: Time available to plan the maintenance actions related to the inspection frequency of program 5 in weeks

The percentage a certain maintenance planning is used differs. In the figures, it is seen that the number of OPM reduces, increasing the percentage of PM. Also, the time on average available to plan the maintenance actions decreases when the time between samples is increased, presented in table 6.9, indicating that the damage is detected at a later stage.
In programs 1 and 2 the increase in time between samples results in higher levels of unexpected breakdowns. This is not the case with program 5. Program 5 only has a difference between the percentage

of OPM and PM. This difference is related to the use of two different PdM program applications. The inspections are combined with an online monitoring option. So, when the time between inspections is high, the chance of detecting damage using the monitoring system increases. The monitoring application used in program 5 is the Banner application. The banner application is only able to detect stage 3 and 4 damage. Due to this, the damage detected with the online application will result in PM or EPM. When the time between inspections increases, it becomes more likely that the damage is detected using the monitoring program resulting in the shift from OPM to PM. This difference is not visible in the overall cost because the cost related to OPM and PM are very similar.

**Conclusion test 4**

The overall conclusion from test 4 is that the inspection interval strongly influences a PdM program's overall cost or reliability. In the case of PdM programs 1 and 2 a smaller inspection interval will result in a higher chance of detecting the damage. Reducing the number of unexpected breakdowns and increasing the reliability. As a result, the overall cost will be reduced.

For PdM program 5, the overall cost is less affected by the inspection interval than programs 1 and 2. Because the inspection only detects the damage earlier, the online condition monitoring application prevents unexpected breakdowns. The difference in cost is not that evident for an earlier stage detection, but this does influence the reliability and especially the time available to plan the maintenance actions.

So, in general, it can be concluded that the inspection interval influences the cost-effectiveness of the discontinuous programs. A shorter inspection interval will result in higher reliability. Which in some cases leads to a reduction in cost.

### 6.4.5. Overall results: ”worst-case” scenario

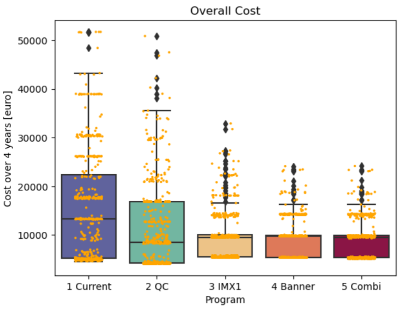
Using the insight gathered through conducting the test, an overall result will be given. In combination with the test's conclusions, this overall result will be used to advise on the most cost-effective PdM program. The overall results will be the results of a ”worst-case” scenario. This scenario is used to assess the effect of combining the different influences on the outcome.

The ”worst-case” scenario uses the options for the influences which are most likely or have the greatest influence on the outcome. The following information is used.

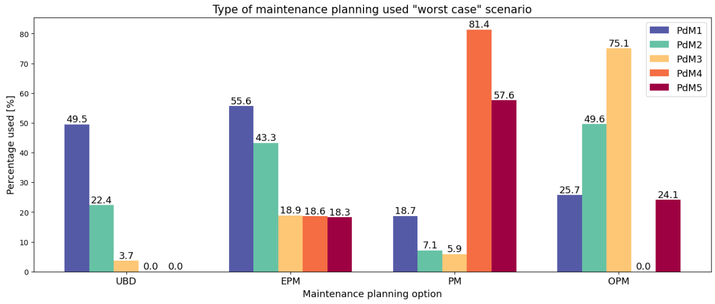
- **Alarm condition:** The literature-based alarm conditions will be used. These alarm conditions result in less reliable situations than practice-based alarm conditions. Also, the other influences show the most effect when the literature-based alarm conditions are used.
- **Failure distribution:** Although the test shows some difference, the decision is made to use the failure distribution, which is most related to the information provided, the general failure distribution. This failure distribution combines the different options.
- **ON/OFF ratio:** The ON/OFF ratio of pump 3 will be used. Pump 3 is 7.2% of the time ON, the lowest option.
- **Inspection interval:**The following inspection intervals will be used, these are most likely to be used when the programs are applied. Program 1: 4-month, Program 2: 2-month, Program 5: 4-month.

Using the ”worst-case” scenario in the simulation cost model generates the following results. The overall cost is presented in figure 6.14a, and figure 6.14b presents the type of maintenance planning used and the percentage of unexpected breakdowns. Table 6.10 presents the average cost per year, the difference in overall cost compared to the current situation, the percentage of an unexpected breakdown has occurred, the percentage a specific maintenance planning is used and the average time for planning in weeks.

The ”worst-case” scenario results show that program 1 has the highest overall cost, followed by program 2. Both these programs have a high overall cost but also a high percentage of unexpected breakdowns. Both programs are level 2 programs, discontinuous.




(a) Overall cost related to "worst case" scenario




(b) Maintenance actions related to "worst case" scenario

Figure 6.14: Overall cost and reliability results "worst case" scenario

| | **Average cost per year [€]** | **Difference overall cost*** | **%UBD**** | **%EPM**** | **%PM**** | **%OPM**** | **TTP*** [weeks]** |
|---|---|---|---|---|---|---|---|
| PdM 1 | 3911.1 | 0% | 49.5% | 55.6% | 18.7% | 25.7% | 1.9 |
| PdM 2 | 2790.3 | -31% | 22.4% | 43.3% | 7.1% | 49.6% | 5.8 |
| PdM 3 | 2359.8 | -40% | 3.7% | 18.9% | 5.9% | 75.1% | 6.3 |
| PdM 4 | 2203.4 | -44% | 0.0% | 18.6% | 81.4% | 0.0% | 4.4 |
| PdM 5 | 2187.4 | -44% | 0.0% | 18.3% | 57.6% | 24.1% | 5.1 |

* Is the difference in overall cost related to the current situation, a negative value represents a reduction in overall cost.
** UBD: Unexpected breakdown, EPM: express planned maintenance, PM: planned maintenance, OPM: optimal planned maintenance. The percentage indicate the occurrence of the maintenance type in the 500 repetitions.
*** TTP: Time to plan the maintenance actions in weeks

Table 6.10: Numerical results "worst case" scenario

The other three programs, programs 3, 4, and 5 have similar overall costs. However, with program 4, 3.7% of the maintenance actions are due to an unexpected breakdown and zero for the other two programs.
The main difference between programs 4 and 5 is the time available to plan the maintenance actions. For program 4, this is 4.4 weeks, while for program 5, this is 5.1 weeks. The time to plan the maintenance actions has increased due to the ability to detect failure earlier with the inspections added to the PdM program in program 5.

## 6.5. Discussion

In this section, the results of the 4 tests and the ”worst-case” scenario are discussed.

The main noticeable difference in the results is the difference between programs 1 and 2 and programs 3, 4, and 5. In most cases, the cost for programs 1 and 2 are higher, and also, the percentage of unexpected breakdowns that have occurred during the 500 repetitions increased compared to the other programs. This difference is a direct result of the different maturity levels. Programs 1 and 2 have a level 2 maturity, making them discontinuous programs. While programs 3, 4, and 5 are continuous programs due to online monitoring applications related to a maturity level 3 or 3 plus. These results are as expected. In PWC and Mainovation [23] the levels are related to the amount of data they use and their reliability. In [23] the reliability of a level 2 program is lower compared to programs with a higher maturity level.

Discontinuous programs are less reliable because they gather less data, resulting in the inability to get a complete picture of the assets condition. The effect of data samples on the reliability is also visible in test 4, analysis of the inspection interval. If the time between the inspections increases, there is a higher chance the damage is missed or detected in a late stage. Resulting in an unpredictable situation.

The reliability of program 2 is higher than the reliability of program 1. Program 2 is executed by in-house mechanics, making it possible to decrease the time between inspections. This increase the ability to detect the damage.

Programs 3, 4, and 5 use an online monitoring application, resulting in level 3 or 3 plus programs. The programs are expected to have higher reliability, related to the information provided in [23]. This is also seen in the results. The percentage of unexpected breakdowns that occurred in the simulation model is reduced a lot when one of the three continuous programs is used. Due to the high sample frequency of online monitoring programs, the damage can be detected in time. The program can gain a complete picture of the condition of the asset.

However, due to the discontinuous operating profile of the asset, a continuous program can become discontinuous when only looking at the useful samples. This was analysed in test 3, the effect of ON/OFF ratios. The discontinuity of the asset can increase the time between useful samples. If the damage evolves at a fast rate, this could become a problem. This problem occurred when program 3 was applied to pump 3 with a low ON%, combined with the literature-based alarm conditions. With the literature-based alarm conditions, the damage evolvement rate depends on the EoL selected [26]. If the EoL is short, the damage will evolve fast. Program 3 is influenced by this aspect because the IMx1 program used has a relatively long time between the samples, 3 hours. It is essential to take the relation between the sample frequency and the discontinuous operating profile into account when a program is selected.

Besides the effect of the discontinuous program, there is also a difference in the detect-ability of the continuous programs. The detect-ability indicates which stage of damage the program can detect. The Imx1 application, used in program 3, can detect damage stages 2, 3 and 4. While the Banner application used in programs 4 and 5 can only detect damage of stages 3 and 4. This difference results in a difference in the time to plan the maintenance actions. If the damage is detected earlier, there is more time to plan the maintenance actions. Program 3 has the longest average time to plan the maintenance actions.

In program 5, the Banner application is combined with inspections using the Quick Collect. The Quick Collect can detect damage of stages 2, 3, and 4. Due to this combination, the reliability of the program is higher than program 4. The main difference is that at certain points in time, the detect-ability of the program increase. This is due to the sample interval of the Quick Collect.

The effect of the Quick Collect is assessed in test 4, the inspection interval. In this test, the sample interval of the quick Collect is adjusted. In the results, a difference became clear, a shorter inspection interval increases the detection of damage in the early stages, increasing the time available to plan the maintenance actions. These results are in line with expectations.

The other two influences not directly related to the program are the failure distribution and the alarm conditions. They both influence the programs but cannot be altered by changing the program. The failure distribution has an impact on the outcome of the results. The numerical values of the results differ, but the ratio between the programs is not always affected. As long as the probability of a failure occurring is the same, the type of failure distribution will not highly influence the ratio between the programs. There will be a small difference, but in general, the same trend can be seen. The probability of a failure is an essential aspect since it is directly related to the overall cost. In the case of No failure, the overall cost will solely be a function of the PdM program cost. It is important to determine how likely it is that the asset will fail before applying the program. A failure is required to gain the benefits of an advanced PdM program. This is why it is important to assess the critically of the asset. The critically focuses on the effect of a failure but should also assess how likely it is the asset will fail.

The last aspect that is of importance is the alarm conditions. These form an essential aspect of the simulation cost model. However, it is difficult to determine which option is most suited. There are two options assessed in this thesis, literature-based and practice-based. The options influence the outcome of the simulation model. In general, the difference between the programs and the effect of the influences is minor when the practice-based alarm conditions are used, compared to the literature-based alarm conditions. However, it is important to use both options to generate results due to the uncertainty in the alarm conditions. Further research should focus on determining the best alarm conditions for the evolvement of bearing damage.

## 6.6. Limitations

Besides discussing the results, a few limitations of the model will be discussed. The first limitation is related to the specific design of the simulation cost model. The model is developed for the case study, thus completely focused on the vacuum compressor pumps. This could influence the ability of the model to assess PdM programs for other assets. The main aspect is that the model is based on the different stages of bearing damage. So it can be expected that the model can be used for other assets as long as bearing failure is the focal point of the PdM program. Also, it is vital to change the input data for the asset in question.

The second limitation is the cost model. The cost in this simulation cost model is built up of three categories. The cost related to maintenance actions, the cost related to downtime, and the PdM program cost. It is essential to know that multiple aspects could also influence the overall cost. For instance, the cost related to inventory, the cost for different failure modes, the cost for planned downtime, the indirect cost linked to the maintenance staff performing the inspections. These aspects can be added to the simulation cost model, but further research is required.

Another aspect that should be taken into account, the simulation model is limited to the optimal execution of the PdM program. In the simulation cost model, the data collected is inspected by in-house staff until damage occurs and a deviation is detected. If this happens, the data will be inspected by the experts at Facta to get more in-depth information out of it. In the simulation, if Facta inspect the data, there will always be damage detected. This means the data is always interpreted correctly by the in-house staff. However, in practice, this might not always be the case, certainly not in the beginning. It takes some time to get familiar with the trends and detecting when it could be an false alarm and when the damage starts to develop. Due to this, the cost related to the PdM programs might be higher, especially in the beginning.

The final aspect that should be discussed is the completeness of the results. The simulation cost model focuses on the detect-ability and sample frequency of the PdM programs and the effect on the cost-effectiveness. However, besides these aspects, it is essential to consider aspects not included in the simulation. Such as the option to extend the PdM program to other assets, the ability to incorporate other data of the process, the application requirements, the ability to increase the maturity level with the same system and the benefits of performing inspections. These aspects are outside this project's scope but should be included when deciding on a PdM program, for instance, by using a SWOT analysis. The simulation should be used as part of the assessment and not as the complete assessment of the options.

## 6.7. Conclusion

The information in this chapter is used to answer the fifth sub-question. The simulation cost model can give insight into the cost-effectiveness of PdM programs for the vacuum compressor pump by analysing 4 influences and a ”worst-case” scenario. The 4 influences are alarm conditions, failure distribution, ON/OFF ratios, and inspection interval. The results of the tests are used to form the ”worst-case” scenario. The ”worst-case” scenario and the information on the influences will give insight into the KPIs, overall cost and reliability, which can be used to advise on the cost-effectiveness of PdM programs. However the simulation should be used as part of the assessment and not as the complete assessment of the options.

# 7 Conclusion

This thesis is conducted to advise Duyvis on how to apply predictive maintenance to the vacuum compressor pumps in the most cost-effective way.

It can be concluded that predictive maintenance is applied using a PdM program. PdM programs come in a wide variety of application options and maturity levels. The use of a focus point for application makes it possible to narrow down the options. For the vacuum compressor pump, the focus point for predictive maintenance are the 4 different stages of bearing damage, assessed using a level 2, 3 or 3 plus PdM program. This resulted in different programs that are assessed on their cost-effectiveness by focusing on the overall cost and reliability.

To be able to select the most cost-effective PdM program for the vacuum compressor pump, it is concluded that a simulation tool should be developed. The tool will be used to gain insight into the effect of the sample frequency and the detect-ability of PdM programs on the overall cost and reliability. A DES model is selected to give insight into the reliability related to the application of the program over 4 years. Also, the output of the DES model will be used as input for the cost model. Which can determine the overall cost by taking the maintenance, unplanned downtime and PdM program costs into account.

Throughout the research, it became clear that different aspects could influence the cost-effectiveness of a PdM program. Due to this, the simulation cost model is used to analyse the effect of 4 different influences on the overall cost and reliability. The 4 influences are the alarm conditions, failure distribution, ON/OFF ratios and inspection interval.

In general, it can be concluded that the 4 different influences impact the outcome of the simulation cost model. The extend of the influence depend on the program and the specific situation. Besides analysing the 4 influences separately, they are also combined in a ”worst-case” scenario. Which is used to determine the most cost-effective option. The option that is cost-effective in the worst-case scenario is expected to be cost-effective in other scenarios.

Using all the information provided in this research, it can be concluded that program 5 is the most cost-effective program for application on the vacuum compressor pumps at Duyvis. The answer on the main research question.

Program 5 combines a continuous online Banner application with the inspections conducted with the Quick Collect. combining these aspects gives the ability to combine high sample frequency with high detect-ability.

PdM program 5 is the most cost-effective option for the vacuum compressor pumps because, in the ”worst-case” scenario, it increases the time to plan the maintenance action by 3.2 weeks and eliminates the occurrence of unexpected breakdowns. While reducing the average cost per year by 44% compared to the current situation. Besides these results of the ”worst-case” scenario, program 5 is least affected by the 4 different influences.

The application of program 5 is in line with level 3 plus maturity. The new maturity level added in this thesis. It can be concluded that this new level is the most cost-effective option. Inline with the increase in reliability with the increase of data [23]. However, it is essential to assess the ability to apply level 3 plus application to other sectors.

Besides introducing a new level, it can also be concluded that a tool has been developed that can assist decision-makers in selecting the most cost-effective PdM program for a situation. Currently, the literature focuses on selecting a maintenance strategy or policy. There is a lack of information on the selection of PdM programs. With this research, this gap in the literature is partially closed by developing a simulation cost model. The gap is only partially closed since the simulation cost model is specifically developed for the vacuum compressor pumps at Duyvis and can only assess PdM programs that focus on detecting the different stages of bearing damage.

## 7.1. Further research

In this thesis a simulation cost model is developed that is used to give advice on the most cost-effective PdM program for the vacuum compressor pumps at Duyvis. The following aspects could be the focus of further research

The simulation cost model developed in this research is specifically designed for the vacuum compressor pumps at Duyvis. Due to this, it is uncertain how the model can assess PdM programs for different assets. It is expected that applying the model to other types of assets will not form a problem. As long as there is enough information for the input available and the PdM program focuses on bearing damage. This is related to how the simulation model is built up. It uses the different stages of bearing damage for the alarm conditions.

In this research, the new proposed level, level 3 plus, is the most cost-effective option. Further research could focus on applying level 3 plus programs in different sectors or on different assets. Also, different application programs for level 3 plus could be analysed. Further research should prove that level 3 plus is a cost-effective option for multiple applications and should be placed above level 3 in the maturity matrix presented by PWC and Mainovation.

The final aspect that is recommended to assess further is the simulation cost model. The first aspect that should be taken as the focus of further research is the validation of the model. Currently, this is not done due to the lack of data available and the inability to compare it with other studies due to the gap in the literature. A case study could be used to analyse programs and at the same time implementing the programs. The results of the implementation can be used to validate the model.
Besides the validation, further research could also focus on the limitations of the model. Further research could focus on extending the cost model, including the inaccuracy of detection and assessing other techniques that could be combined with the simulation cost model to gain a complete overview of all the aspects of a PdM program.

**Further research Duyvis**

Besides the further research options related to the development of the simulation model and the level 3 plus option, there are also steps that Duyvis should take. The simulation model results indicate the most cost-effective PdM program, but as already presented, the results only take the cost-effectiveness related to the sample frequency and the detect-ability into account. The results of the simulation model should be combined with a SWOT to come to an overall conclusion. The PdM program selected will be applied using a proof of concept. The proof of concept can be used to gain insight into the application of the PdM program. Information gathered during the proof of concept, combined with all the information of the simulation cost model, will result in the ability to make a well-informed decision.

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# A

# Scientific paper

# A simulation cost model to analyse the cost-effectiveness of predictive maintenance programs.

A case study for the vacuum compressor pumps at Duyvis

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**Abstract**

In this paper, a simulation cost model is presented that can be used to assess the cost-effectiveness of a selection of PdM programs. The proposed model combines a discrete event simulation (DES) model with a cost model. It is specifically designed to analyse the PdM programs for the vacuum compressor pumps at Duyvis. All the PdM programs proposed will work with vibration analysis to detect bearing failure. The simulation model will focus on the sample frequency and detect-ability of a PdM program. The sample frequency is related to maturity levels, and the detect-ability is related to detecting the different stages of bearing damage. The goal is to use the proposed simulation cost model to assess a selection of PdM programs on their overall cost and reliability.

## 1 Introduction

Predictive maintenance (PdM) is the newest maintenance policy there is. It has been introduced due to the possibilities related to big data and wireless communication. PdM is a maintenance policy that uses the condition of the asset to plan the maintenance actions. If PdM is applied correctly, it can improve availability, product quality, safety requirements, and operating cost levels of the production plant [8]. Due to these promising benefits, there has been an increase in interest in PdM over the years. In line with the interest, there has also been an increase in the PdM programs available on the market. Which has made it increasingly difficult for decision-makers to select the most suited PdM program for a certain situation.

In the literature, maintenance selection problems are commonly discussed. Even (simulation) tools are developed to analyse the cost-effectiveness of maintenance strategies and policies [1, 2]. However, there is a lack of information ad tools available that can be assists decision-makers in selecting a PdM program. This gap in the literature will be partially closed in this research. In this research, a simulation cost model is proposed that can be used to gain insight into the cost-effectiveness of PdM programs.

**Case study: Duyvis**

This research has been conducted as a case study for the vacuum compressor pumps at Duyvis. Duyvis wants to enhance their PdM program, but they want to make a well-informed decision. Due to the case study, the simulation cost model proposed will be specifically designed to analyse the cost-effectiveness of PdM programs for the vacuum compressor pumps.

**Cost-effectiveness**

In this research, the cost-effectiveness is related to the overall cost, KPI 1. The overall cost is a function of the cost related to the PdM program, the maintenance actions and the unplanned downtime. The second KPI to analyse the cost-effectiveness is the reliability, related to the number of unexpected breakdowns. But, also the type of maintenance planning used and the time available to plan the maintenance actions.

**Outline of the research**
The main goal of the research is to develop a simulation cost model that can be used to analyse different PdM programs for the vacuum compressor pumps at Duyvis.
To reach this goal, first, some general information on the application of PdM is presented. Followed by information on the programs that are assessed and the focus point of the simulation model. This information is used to propose the model in section 4 and the results of implementing the simulation model on the case study will be presented and discussed in section 5.

# 2 PdM in Industry

The first step is to gain some background knowledge on the application of PdM in practice.
In practice, the way maintenance actions are approached and planned is related to a maintenance strategy. A maintenance strategy is built up of maintenance policies. There are three main maintenance policies, corrective, preventive and predictive maintenance (PdM). This research focuses on PdM. PdM uses the condition of the asset to plan the maintenance actions accordingly. A PdM policy is applied using a PdM program. PdM programs come in various application options. However, the structure is, in general, the same.

A PdM program consists of three main parts [4]. Decisions related to these aspects have to be based on the type of situation where the program is applied.

1. **Data Acquisition:** Gathering data of the asset.
2. **Data Processing:** Analysing the data to give insight in the condition of the asset
3. **Decision making:** Using the information on the condition of the asset to determine how the maintenance actions should be planned.

The different PdM programs can be classified using maturity levels. In research performed by PWC and Mainovation [7]. 4 different maturity levels are introduced.

- **Level 1 Visual inspections:** Physical periodic inspections done on a periodical basis. The conclusions are only based on the expertise of the inspector.
- **Level 2 Instrument Inspection:** The periodic inspections are now done with the use of an instrument. The conclusion is based on a combination of the inspector's expertise and the data gathered with the instrument.
- **Level 3 Real-time condition monitoring:** (semi)continuous real-time monitoring of assets. The conclusions are now solely based on data. The alerts are based on pre-established alarm levels.
- **Level 4 PdM 4.0:** (semi) continuous real-time monitoring of assets. The conclusions are solely based on data. However, the alarms are now based on predictive techniques, such as regression analysis.

Besides these 4 levels, a new level is added in this research, level 3 plus. Level 3 plus combines a level 2 program with a level 3 program. Combining the programs can give the ability to keep the benefits if a less mature level when moving to a more technical advance option [6]. In figure 1 contains a graphical representation of the levels.

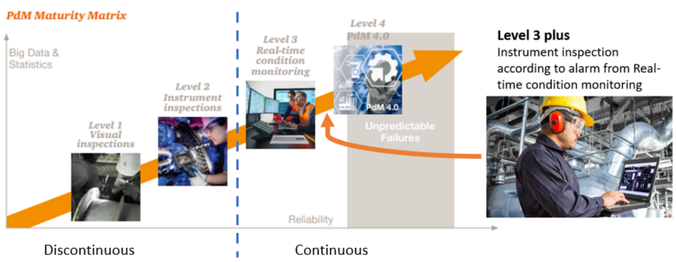



Figure 1: PdM maturity levels, based on [7]

## 3 PdM programs for Duyvis

The simulation model is specifically developed to analyse the PdM programs for the vacuum compressor pumps at Duyvis. Currently, the vacuum compressor pumps are maintained following a level 2 PdM policy. The PdM program consists of 3 inspections per year performed by an external party. Duyvis wants to change its application to reduce the overall cost and increase the reliability. These two aspects form the KPIs when analysing the programs. First, the focus point for the simulation has to be determined, and a selection is made on the programs.

The vacuum compressor pump at Duyvis is the focal point for the PdM programs. The vacuum compressor pumps are critical assets at Duyvis due to the high impact a failure has on the production process, a 60% reduction of production capacity. Selecting a PdM program for the vacuum compressor pumps is difficult due to the numerous options available, and the pump has a discontinuous operating profile. The effect this has on the different options is uncertain. At Duyvis 4, vacuum compressor pumps are used. The only difference between the pumps is the parentage the asset is ON, 45.8%, 10.7%, 7.2%, and 42.8%.

The PdM programs selected will focus on the vibrations produced by bearing damage. This is done by using an accelerometer for vibration analysis. Vibration analysis detects a vibration pattern, and a deviation of the pattern can indicate damage. In general bearing damage evolves over 4 different stages [3, 5], presented in figure 2.

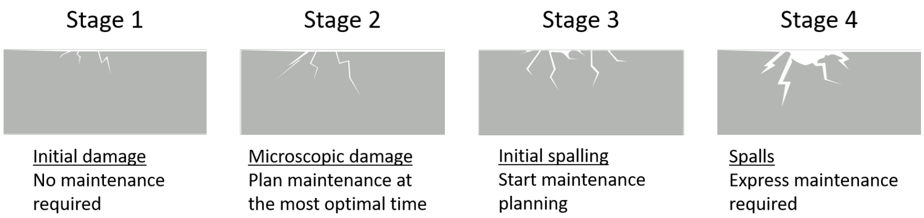



Figure 2: Graphical representation failure stages bearings

- **Stage 1**: Damages start occurring. It is still below the surface and not visible. No direct actions have to be taken at this point. However, it is wise to keep monitoring the damages.
- **Stage 2**: The fault progresses, microscopic damages occur. The advice with a level 2 damage is to plan the maintenance actions for the most optimal time.
- **Stage 3**: The damage becomes more severe. The damages are now resulting in initial flaking, cracking and/or spalling. It is advised to start planning the maintenance actions immediately.
- **Stage 4**: The final stage of bearing failure. Multiple cracks, excessive flaking or spalling is occurring. The bearing should be replaced immediately, express maintenance actions.

The different stages of bearing damage indicate the severity of the damage, which influences the expected time of failure of the bearing and how the maintenance action should be planned. In this research, there are 3 different planning options for the maintenance actions. These different options indicate the time needed to plan the maintenance actions and have different cost aspects. The three options are:

- OPM: Optimal planned maintenance, the maintenance actions will be performed at the optimal moment in time.
- PM: Planned maintenance, the planning of the maintenance actions will start immediately
- EPM: Express planned maintenance, the damage is in a severe stage, and the planning should use express options.

The ability to detect the different stages of damage is related to different aspects of the PdM program, the frequency range and the analysing method used.

The ability to detect the different stages is the detect-ability of a program. It is possible to detect the different stages of damage because they produce different vibration signals, which can be detected using a certain analysing technique. The relation between the stages of damage, the frequency range and the analysing methods is presented in table 1.

| Damage stage | Detection zone | Analysing method | Frequency range |
|---|---|---|---|
| Stage 1 | D | SEE analysis | High (20 to 40 kHz) |
| Stage 2 | C | Envelop spectrum | Medium (up to 20 kHz) |
| Stage 3 | B | FFT spectrum/overall vibration | Low (up to 10 kHz) |
| Stage 4 | A,B,C,D | No requirements | no requirements |

Table 1: Requirements for detection of the damage stages

In general, most aspects related to a PdM program can be selected using requirements and wishes. However, two aspects are difficult to determine, the sample frequency and the detect-ability. The effect they have on the cost-effectiveness when applied to a certain asset is difficult to determine. In general, the minimum requirement can be set, but the effect of a higher sample frequency or detect-ability is not as easily determined. The two aspects are intertwined with each other. For programs of the same price, the sample frequency and detect-ability can differ. An increase in sample frequency will result in a decrease in the detect-ability. To have a higher sample frequency, the frequency range is lowered and the size of the data collected has to decrease, resulting in a lower quality of data. The quality of data influences the analysing method that can be used. Due to this relation, it is difficult to say in advance what the best option is for a certain situation. Is a higher sample frequency required or a higher detect-ability? These aspects will form the basis for the simulation cost model.

The programs analysed using the model are determined using requirements, wishes, preferences, and the insights presented above. 4 different programs are the result. Besides these programs also the current situation will be analysed, program 1. The different programs are presented in table 2. The programs are all supplied by Banner or SKF.

| Program | Name | Level | Sample frequency | Detect-ability* |
|---|---|---|---|---|
| 1 | Current situation | 2 | 3 to 4 Months | 1,2,3,4 |
| 2 | Quick Collect (QC) | 2 | 1 to 3 Months | 2,3,4 |
| 3 | SKF IMX1 | 3 | 3 hours | 2,3,4 |
| 4 | Banner | 3 | 5 min | 3,4 |
| 5 | QC+Banner | 3+ | 1-3Month/5 min | 2,3,4 |

* The ability to detect the 4 different stages of bearing damage.

Table 2: PdM programs

# 4 Proposed simulation cost model

To analyse the PdM programs, a simulation cost model is developed. The simulation cost model partially closes the gap in the literature. Currently, the focus in the literature is on the selection of maintenance strategies or policies. However, there is a lack of information on the selection of the programs. As already discussed, the proposed simulation model will analyse PdM programs for the application on the vacuum compressor pumps. The simulation cost model will focus on the main difference between the options, the sample frequency and the detect-ability. Using the model will give insight into the overall cost and the reliability, the two KPIs.
The proposed simulation cost model combines a discrete event simulation (DES) model and a cost model. The interaction between the DES model and cost model is presented in the figure below. The output of the DES model will either be used by the cost model or will provide insight into the program's reliability, focusing on the number of unexpected breakdowns and the type of maintenance planning used per PdM program. The cost model will use the simulation model's output and cost-related input to determine the overall cost of a PdM program.

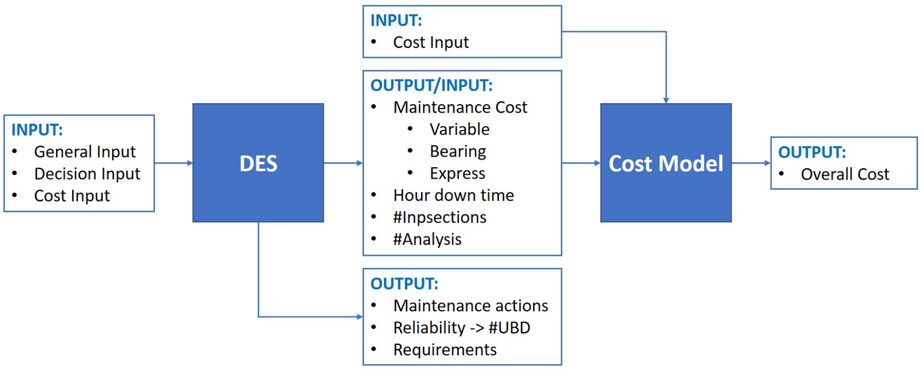



Figure 3: Interaction DES model and Cost model

## DES model

The DES model consists of three components that are used to simulate the maintenance situation.

1. **Machine:** Is used to select an end of life (EoL) time for the asset. Selected from the failure distribution. It will keep the asset running until the EoL is reached, resulting in an unexpected breakdown or until it is interrupted for maintenance actions.
2. **PdM program:** Represents the actions linked to the PdM program. First, the condition of the bearing is determined at the set sample intervals. The condition of the bearing is combined with alarm and maintenance conditions to activate maintenance if required.
3. **Maintenance:** The maintenance component is activated related to the alarm generated. The component will provide information on the cost related to the simulation run and information on the reliability.

There are two aspects of the DES model that are important: the alarm conditions and the failure distribution. The alarm conditions are used to simulate the different detect-ability options of the programs, and the failure distributions will be used to select and end-of-lifetime (EoL)

**Simulation of detect-ability**

The PdM program works with alarm conditions to advise on the type of maintenance planning that has to be used. The alarm and conditions are related to the detection of different stages of damage and the detect-ability. In figure 4, a schematic representation of the information used for the alarm conditions is presented.

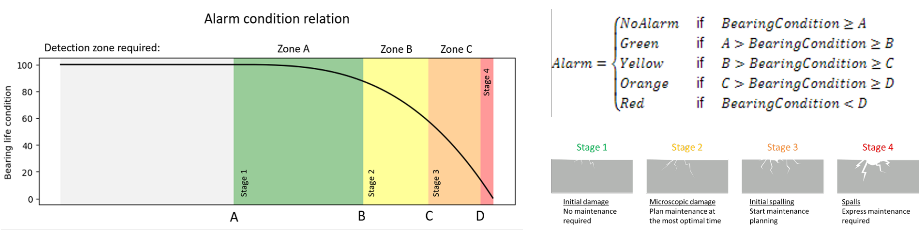



Figure 4: Alarm condition relation relation

The alarm conditions are affected by the type of PdM program used, related to figure 4. The alarm conditions for *No Alarm* will change according to the maximum detect-ability of the PdM program. Damage above this limit will not be detected. The detection zones that cannot be detected with the PdM program will be removed from the alarm conditions. In table 3, an overview is presented on the type of alarms that the different PdM programs can generate.

| **Program** | **No Alarm** | **Green** | **Yellow** | **Orange** | **Red** |
|---|---|---|---|---|---|
| 1 | ✓ | ✓ | ✓ | ✓ | ✓ |
| 2 | ✓ | - | ✓ | ✓ | ✓ |
| 3 | ✓ | - | ✓ | ✓ | ✓ |
| 4 | ✓ | - | - | ✓ | ✓ |
| 5 | ✓ | - | ✓ | ✓ | ✓ |

Table 3: Alarm options per PdM program

The alarm conditions presented need information on the numerical values, A, B, C and D. These numerical values are related to the life left in the asset. There are two different options for these numerical values. They are based on the information provided in the literature or on the information used in practice.

In the literature, the different stages of damage are related to a percentage of life left in the bearing, while the information used in practice is related to months. Using the information provided in the literature, the rate of the evolvement of damage will be related to the end of life (EoL) of the asset. This is not the case with the information used in practice. Here the rate of evolvement is always the same. In the table below, the different options are presented. When analysing the PdM programs, both options will be taken into account.

| **Based on** | **A** | **B** | **C** | **D** |
|---|---|---|---|---|
| *Literature* | 20% life left | 10% life left | 5% life left | 1% life left |
| *Practice* | 5 Months | 2.5 Months | 1.25 Months | 0.25 Months |

Table 4: numerical values alarm conditions

**Failure distribution**

The second aspect of importance is the failure distribution. The failure distribution presents the probability that the asset will fail at a certain time. Information provided by Atlas Copco is used to form a general failure distribution, presented in figure 5. The failure distribution consists of 1) Failures related to infant mortality, related to poor manufacturing. 2) Failures related to improper handling and maintenance, based on the guarantee period, and 3) Failures due to old age, wear out. In this failure distribution, the assumption is made that the probability the asset will fail within the simulation time of 4 years is 100%. The effect of different failure distributions on the outcome of the simulation model will be assessed.

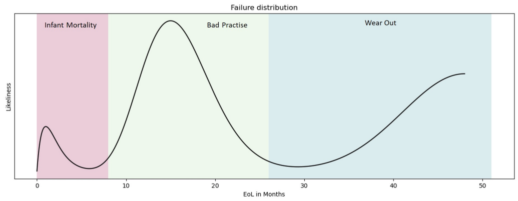



Figure 5: Failure distribution

## Cost Model

The results of the DES model will be used to gain insight into the reliability of the PdM program. However, it will also be partially used in the cost model. The cost model consists of three parts. The cost related to maintenance actions, unplanned downtime, and the PdM program.
The complete cost model is as follows:

$$\begin{aligned} Cost &= C_M + C_{DT} + C_{PdM} \\ C_M &= C_{Fixed} + C_{Variable} + C_{Bearings} + C_{Express} \\ C_{DT} &= \#HourDT * C_{DTHour} \\ C_{PdM} &= CAPEX_{PdM} + OPEX_{PdM} \end{aligned}$$

**Maintenance cost ($C_M$)**
The maintenance cost is a function related to the maintenance activities. Equation 1 presents the equation used to determine the maintenance cost.

$$C_M = C_{Fixed} + C_{Variable} + C_{Bearings} + C_{Express} \quad (1)$$

In this equation, $C_{Fixed}$, is related to the fixed cost for servicing the vacuum compressor pump. The overall cost for all the activities related to the revision is €3400.
The second aspect, the $C_{Variable}$, is the cost related to the secondary damage, damage to other parts of the asset. The amount of damage and if secondary damage will occur depends on the time of detection, related to the damage stage. The variable cost will start to increase from halfway through stage 3. The cost will linearly increase from €0 to €2000. $C_{Bearings}$ is the cost of the bearings that have to be bought, €169.79. The cost of express delivery is €150.

**Down Time Cost ($C_{DT}$)**
The second aspect that is taken into account is the cost related to unplanned downtime of the asset, $C_{DT}$. The downtime of an asset is the time the machine is not able to operate due to damage. The equation used for this aspect is presented below.

$$C_{DT} = \#HourDT * C_{DTHour} \quad (2)$$

In this equation, the number of hours the machine is down, $\#HourDT$ is multiplied by the cost per hour downtime, $C_{DTHour}$, this is for Duyvis €130 per hour. The hours' downtime is the difference in time required to plan the maintenance actions and the life left in the asset at detection time. When the damage is detected in an early stage, the downtime will be zero. In the case of an unexpected breakdown, the downtime will be the time required to plan express maintenance, 2 days.

**PdM program costs ($C_{PdM}$)**
The third aspect of the overall cost is the cost related to the PdM program, $C_{PdM}$. The cost of a PdM program is divided in CAPEX and OPEX costs and these differ per program. To calculated $C_{PdM}$ equation 3 is used.

$$C_{PdM} = CAPEX_{PdM} + OPEX_{PdM} \quad (3)$$

The $CAPEX_{PdM}$ refers to the cost related to the investment of the PdM program []. The investment of the hardware is taken into account in this simulation model. $OPEX_{PdM}$ refers to the cost related to the day-to-day operation of the PdM program []. Multiple aspects can be taken into account when referring to the OPEX. In this research, three different aspects are taken into account.

1. The cost related to the maintenance of the program, for instance, the cost for new batteries.
2. The cost for collecting the data, related to the number of samples taken.
3. The cost related to analysing the data, a function of the times the data is analysed by external experts.

Combining these aspects results in equation 4.

$$OPEX_{PdM} = C_{maintenancePdM} + \#Inspections * C_{Inspections} + \#Analysis * C_{Analysis} \quad (4)$$

The cost related to the PdM program differs per application. In table 5 the cost related to the PdM programs assessed are presented.

| | **PdM program** | | | | |
|---|---|---|---|---|---|
| **Cost aspect** | 1 | 2 | 3 | 4 | 5 |
| $CAPEX_{PdM}$ | €0 | €28 | €1355.5 | €931.05 | €940.65 |
| $C_{MaintenancePdM}$* | €0 | €0 | €0 | €66.6 | €66.6 |
| $C_{Inspections}$ | €40 | €0 | €0 | €0 | €0 |
| $C_{Analysis}$ | €0 | €53 | €53 | €53 | €53 |

* Maintenance cost related to the PdM program over 4 years

Table 5: Cost input PdM programs

## 4.1 Assumptions

In the simulation cost model the following assumptions are used.

- The maintenance actions will result in a as-good-as new situation
- The data will be analysed by in-house staff, there is no extra cost related to this
- The program is 100 accurate in generating alarms for damage
- The asset will fail at least once during the application period of 4 years
- The asset will always fail due to bearing problems inside the pump
- The asses is always ON when inspections are done

# 5 Results

The proposed simulation cost model is used to analyse the cost-effectiveness of the proposed PdM programs for the vacuum compressor pumps. The focus will be on reliability and overall cost. Before using the simulation cost model, it is vital to gain insight into the aspects that could influence the outcome. In most cases, based on the information that is uncertain of specific characteristics of the asset where it is applied. In this research, the focus will be on 4 influences.

- The inspection interval of a discontinuous application
- The failure distribution
- The ON/OFF conditions of the asset
- The alarm conditions

The overall cost of the programs will be determined by analysing the cost over the simulation time for multiple repetitions. The cost of all the three different cost categories will be combined. The reliability will be related to the percentage of times an unexpected breakdown occurred over the repetitions. The same is done for the different maintenance types. Also, information on the time to plan the maintenance actions will give insight into the reliability.

To analyse the cost-effectiveness of the different PdM program options. Tests are done related to the four aspects that could influence the PdM program. These different tests gave insight into the effect they have on the overall cost and reliability. The information from these tests is combined to form a "worst-case" scenario. The "worst-case" scenario is built up using the information provided in the tests. The influences are selected as either being most likely or due to the highest effect.

**Test 1: Alarm conditions**
The alarm conditions used in the simulation cost model can be based on information found in the literature or used in practice. The effect this has on the model's outcome will be analysed by implementing both options to the same situation.
Using the information provided in the test, it can be concluded that the two different alarm conditions influence the model's overall outcome. The main difference between the alarm conditions is that all the programs are more reliable when the alarm conditions are based on practice. There are fewer unexpected breakdowns and EPM used. Both options will be used to assess the other influences in the remaining tests, due to the difference between the options and the inability to select the most suited one,

**Test 2: Failure distribution**
There is high uncertainty about the exact failure distribution of the pumps. Due to this, 7 different failure distributions have been used to run the simulation. In general, the ratios between the options are similar, but one crucial aspect changes the outcome. The probability the asset will fail within the simulation time. If the asset does not fail, there are no benefits, only cost related to the program, which is unfavourable for the continuous programs. If the chance the asset will fail within the simulation time increases, the continuous programs become more cost-effective since the benefits start to play a role.
Using this information, one general conclusion can be made. It is important to get a general idea of the failure distribution of the asset. The most important aspect to know is the probability that the asset will fail during the program's life cycle.

**Test 3: ON/OFF ratios**
The PdM program selected will be applied to 4 vacuum compressor pumps. The pumps are identical, but they have different operating profiles resulting in different ON/OFF ratios. The different ON/OFF ratios have been implemented to the model to assess the effect on the online monitoring programs, programs 3, 4, and 5.
Based on the test results, it can be concluded that only program 3 is influenced by the different ON/OFF ratios. However, the extent of the influence is highly influenced by the alarm conditions. When the alarm conditions are based on literature, the influence is more severe, the chance of an unexpected breakdown increases from 0.2 to 3.7% for pump 3. Compared to an increase from 0 to 0,1% for pump 3 when practice-based alarm conditions are used. Although the exact extent of the

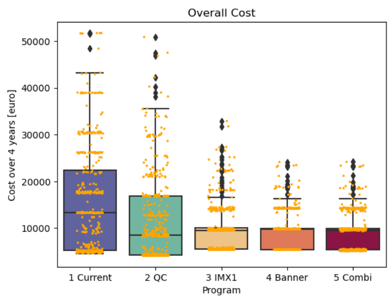
ON/OFF influence is unclear, it is still a factor that should be considered when decisions are made on the most cost-effective PdM program.

**Test 4: Inspection Interval**

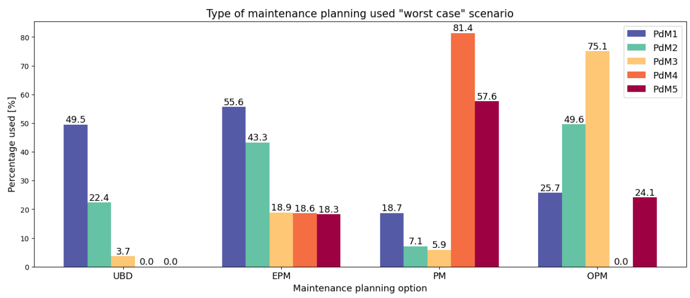
The discontinuous programs use inspections to gather the data. The frequency can easily be adjusted. The results of altering the inspection interval on the cost-effectiveness are as expected. In general, it can be concluded that the inspection interval influences the cost-effectiveness of the discontinuous programs. A shorter inspection interval will result in higher reliability. Which in some cases leads to a reduction in cost. However, it is essential to consider aspects not incorporated in the simulation cost model, such as the time required for the inspections.

**Overall results: "Worst-case" scenario**

Besides the 4 tests also, a "worst-case" scenario is analysed. The "worst-case" scenario is built up using the information provided in the tests. The alarm conditions are based on literature, the failure distribution is based on the information provided by Atlas Copco, the asset will 100% fail within the 4 years simulation time, the asset is 7,2% of the time ON, and the inspection interval of programs 1, 2, and 5 are respectively, 4, 2 and 4 months. Figure 6a contains a box-plot representing the overall cost over the simulation repetitions. In Figure 6 the percentage a specific maintenance action has occurred is presented. Both figures give insight into the overall cost-effectiveness of the program. The results of the "worst-case" scenario is also presented in table 6. The table contains the average cost per year, the difference in overall cost related to the current situation, the percentage of unexpected breakdowns, similar for the other maintenance types and finally, the average time to plan the maintenance actions.



(a) Overall cost "worst case" scenario



(b) Maintenance actions "worst case" scenario

Figure 6: Overall cost and reliability results "worst case" scenario

| | **Average cost per year [€]** | **Difference overall cost*** | **%UBD**** | **%EPM**** | **%PM**** | **%OPM**** | **TTP*** [weeks]** |
|---|---|---|---|---|---|---|---|
| 1 | 3911.1 | 0% | 49.5% | 55.6% | 18.7% | 25.7% | 1.9 |
| 2 | 2790.3 | -31% | 22.4% | 43.3% | 7.1% | 49.6% | 5.8 |
| 3 | 2359.8 | -40% | 3.7% | 18.9% | 5.9% | 75.1% | 6.3 |
| 4 | 2203.4 | -44% | 0.0% | 18.6% | 81.4% | 0.0% | 4.4 |
| 5 | 2187.4 | -44% | 0.0% | 18.3% | 57.6% | 24.1% | 5.1 |

* Is the difference in overall cost related to the current situation, a negative value represents a reduction in overall cost.
** UBD: Unexpected breakdown, EPM: express planned maintenance, PM: planned maintenance, OPM: optimal planned maintenance. The percentage indicate the occurrence of the maintenance type in the 500 repetitions.
*** TTP: Average time to plan the maintenance actions in weeks

Table 6: Numerical results "worst case" scenario

Using the information provided in table 6 and the information gathered through the test shows that continuous programs are more cost-effective than discontinuous programs. This leaves programs 3, 4 and 5. These three options could all be cost-effective but there are some small difference that should be taken into account. PdM program 3, the IMx1 option, collects data every 3 hours. This in combination with the discontinuous operating profile of the vacuum pumps makes the IMx1 less robust. Since it is not always possible to detect damage in time using the IMx1, there is a small chance an unexpected breakdown might occur. PdM program 4 on the other hand has a higher sample frequency but is less reliable due to the inability to detect damage of stage 2, which results in less time to plan the maintenance actions.

**Limitations of the model**
Through applying the model some limitations became clear. These should be kept in mind when using the results to decide on the most cost effective PdM program. The limitations are.

- The model is specifically designed for the vacuum compressor pumps at Duyvis. So used the evolvement stages of bearing damage.
- The cost model only focuses on three categories. could be other factors that also influence the overall cost of a program, such as inventory costs.
- The model uses a situation where the program is 100% accurate, this will in practise not always be the case.
- The model only focuses on the sample frequency and the detect-ability of the PdM program. However other aspects could also influence the decision.

These limitation can be used as the basis for further research.

# 6 Conclusion

Using the simulation results, it can be concluded that continuous programs are more cost-effective than discontinuous options. All the 3 PdM programs using online monitoring could be cost-effective and only differ slightly. The difference between the programs is assessed by taking all the aspects affecting the overall results into account.

The conclusion is that PdM program 5 is the most cost-effective option for the vacuum compressor pumps at Duyvis. Applying PdM program 5 will result in an annual average reduction of 44% of the overall cost. Also, the time available to plan the maintenance actions will, on average, increase by 3.2 weeks.

PdM program 5 is cost-effective because it combines the best aspects of two programs. The high detect-ability is related to maturity level 2 in combination with high sample rate of a level 3 program. The new maturity level proposed in the research is as expected, it results in higher reliability due to the combination of the best of two programs. Further research should focus on assessing the possibilities of level 3 plus programs in other sectors or other assets.
In general, it can be concluded that the simulation cost model can analyse the cost-effectiveness of PdM programs. However, it is important to note that the simulation cost model focuses on two aspects related to the PdM program, the sample frequency and the detect-ability. The simulation cost model should be used as part of the selection process and combine the results with other insights.

# 7 Further Research

As already mentioned, the application of level 3 plus programs could be analysed for different sectors and assets.
Besides the level 3 plus, it is also suggested to focus further research on the simulation cost model. The model still needs to be validated, this has not yet been done due to the lack of data. Besides the validation of the simulation model, the limitations could form the basis for further research.

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# B

# Vacuum compressor pump information

## B.1. General information vacuum pump

In this appendix information on the vacuum pump is presented.

The vacuum compressor pump (VCP) used at Duyvis are the BUSCH Mink MM 1322 AV, presented in figure B.1a. These are dry claw pumps. At Duyvis four identical VCP are used for the transportation of flour from a silo to the mixomats. The flour is used to coat the peanuts in the production process. The pumps work with a discontinuous operating profile. More information on this can be found in appendix B.2. All four VCP are critical for the production process since they all are required to get a good mix of different flour types. All four VCP will have work with the same PdM program.

The four VCP are placed next to each other on a separate floor. The mixomats are the only other equipment located on this flour, but are separated by a wall. in figure B.1b the VCP at Duyvis are presented.


(a) VCP

(b) VCP

The VCP has 2 different types of bearings which are used to rotate the claws, the SKF 3309 A and SKF NU 208 ECP. In figure B.2 the location of the bearings are presented. The figure contains a cross section view of the VCP. number 20 in the figure is the SKF 3309 A and number 40 represents the SKF NU 208 ECP.

The pump is powered by an electro motor, the IEC112.

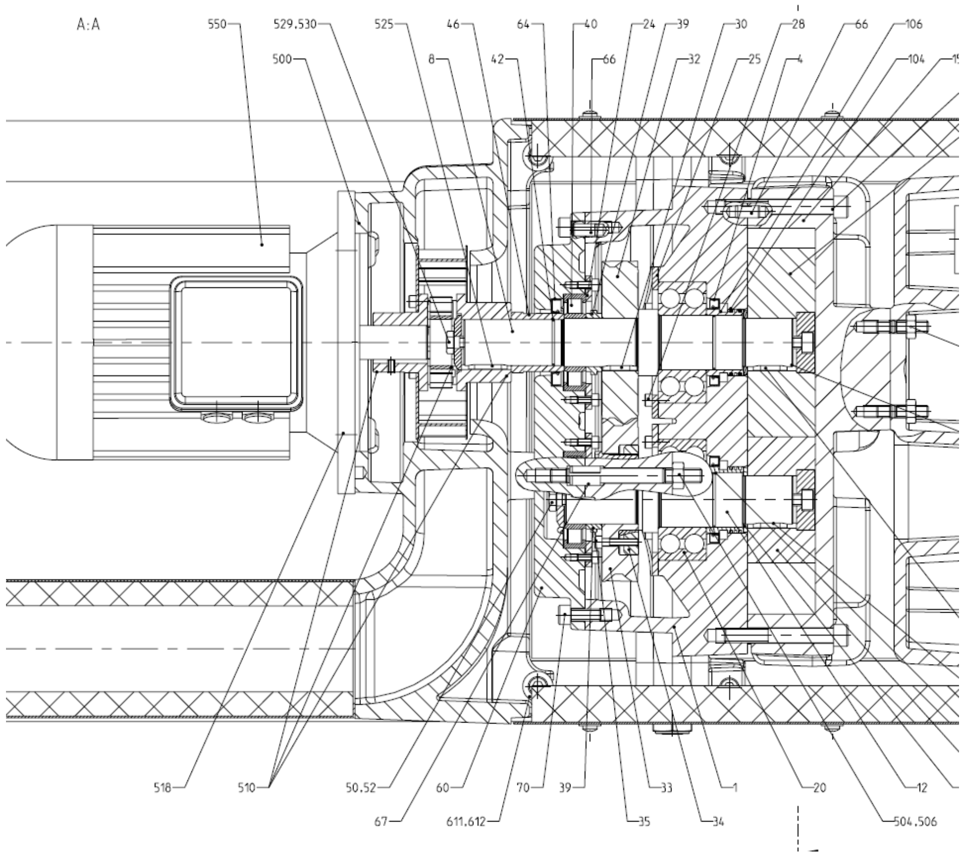
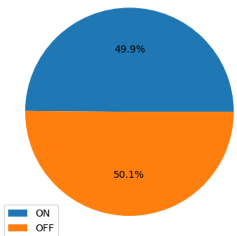


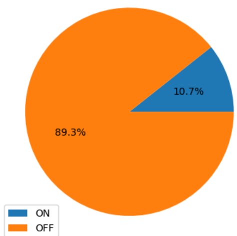

Figure B.2: Bearing location

## B.2. Operating Profile

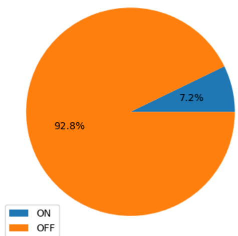
In this appendix more information is provided on the operating profile of the vacuum compressor pump used at Duyvis. The operating profile of the vacuum compressor pumps at Duyvis is trended over time to get insight in the discontinuous operation of the pump. The information used in the appendix is gathered with a PLC analyser which tracked the on and off condition of the vacuum compressor pump for a week. During this week the operation was normal, there where no unexpected events which could have influenced the information. Below the ON OFF ratio of the different vacuum compressor pumps is presented. This information is use din the simulation model to determine the operating condition of the asset.



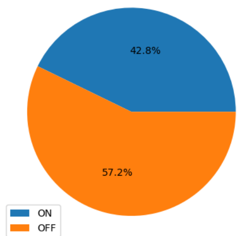

(a) VCP 1




(b) VCP 2




(c) VCP 3

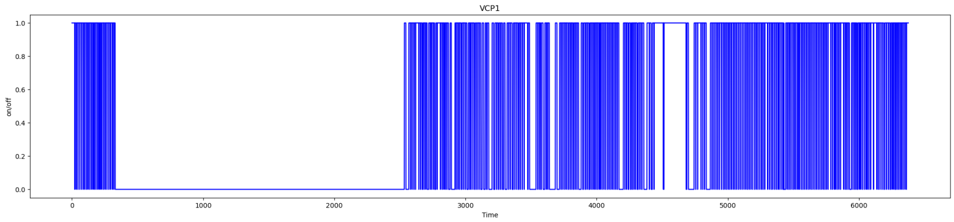



(d) VCP 4

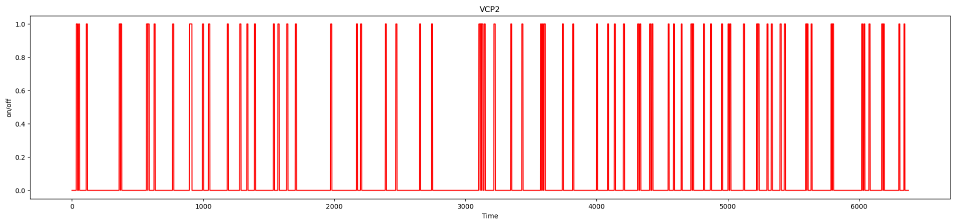
In table B.1 the mean times the asset is on and off are presented. This shows that the time the asset is ON is relatively short. Meaning there is only a short window to collect the data. In the 4 figures below the operational trend for the pumps is presented. From these figures it can be seen that the moment the pump is on or off is random. It depends on the type of flour required for the production process.

| Pump | Mean Time ON [min] | Mean Time OFF [min] |
|---|---|---|
| VCP 1 | 12 | 12 |
| VCP 2 | 9 | 74 |
| VCP 3 | 7 | 87 |
| VCP 4 | 11 | 15 |

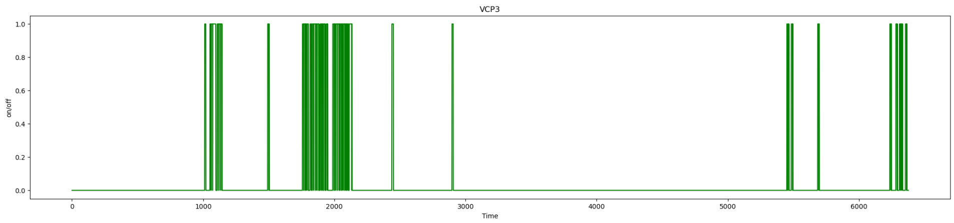
Table B.1: Mean time on and off



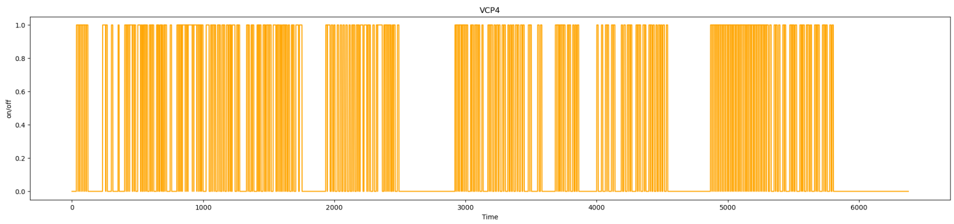

(a) Operation trend VCP 1




(b) Operation trend VCP 2




(c) Operation trend VCP 3




(d) Operation trend VCP 4

Figure B.4: Operation trend vacuum compressor pumps

# C

# Notes Meetings

Notes on the meetings with Rob Visser, Atlas Copco. Wout de Clerck, Atlas Copco. Rob Liefting Busch.

**Notes Meeting Rob Visser from Atlas Copco.**
Attendees:
Rob Visser, service sales engineer Atlas Copco
Laura Mars
Date and Location: 25 May 2021 from 10:00 to 11:00, Online Meeting.
Subject: Failure behaviour of dry claw vacuum compressor pumps.

**Summary:** During the meeting Rob provided general information of failure of vacuum pumps.

**General notes:**
A vacuum compressor pump can be categorized as a claw pump or a vane pump. In general, a vane pump requires more maintenance due to the larger number of rotating parts. But in both cases, it is important to do regular maintenance. The maintenance planning is now made according to the advice given by the manufacturer. This can only be used as an indication because it does not take the operating conditions of the pump into account.

In general, a vacuum pump fails due to blockage or problems with the lubrication of bearings. Also, problems with the electromotor used can occur. A vacuum compressor pump can quickly become a critical asset. But information on the time of failure is difficult to determine. There are multiple aspects that influence the expected life time of the asset.

When assessing the life cycle of the vacuum compressor pumps it is important to assess the probable problems and assess how they can be monitored. In the case of blockage predicting when the failure will occur will be difficult due to the rapid evolvement of the damage related to this problem. Blockage can result in failure in just a few minutes. The result of damage due to blockage is presented in pictures. In the pictures it can be seen that the pump is full with flour that is pulled into the pump due to a tear in the inlet filter due to blockage.

Rob advise is to have a meeting with Wout de Clerck to get more information on the failure distribution of the vacuum compressor pumps.

**Notes Meeting Wout de Clerck from Atlas Copco.**
Attendees:
Wout de Clerck, Service Expert Oil Sealed Screw Pumps and Dry Claw Pumps Atlas Copco
Laura Mars
Date and Location: 21 July 2021 from 16:00 to 17:00, Online Meeting.
Subject: Failure behaviour of dry claw vacuum compressor pumps.

**Summary:** The meeting was done to get more insight in the failure behaviour of dry claw vacuum compressor pumps, Rob Visser from Atlas Copco set up this meeting to get more information. During the meeting it became clear that there is not much data available on this subject, especially due to confidentiality. Although there was not any directly usable data available there was some information presented that can be used to distinguish a failure distribution.

**Is there data available on the failure behaviour of vacuum compressor pumps?**
Atlas Copco is currently trying to get more insight in the failure behaviour of dry vacuum compressor pumps. They use this data to optimize their advice on preventive maintenance. They gather this data by running the machine in a laboratory until it fails. To make this information suitable for the industry a safety factor will be used. Unfortunately, there was no possibility to get insight in the data from the laboratory tests.

**Besides data is there other information that can be used to determine the failure behaviour of the vacuum compressor pump?**
There is not much he can say. But he does advise to think about the guarantee related to the pump. In the case of dry vacuum pumps the guarantee period is in general 1 year. From this it can be expected that the machine will have a higher chance of failing after this year. But it is important to keep in mind that there can always be some damaged that has occurred during the production process.
Also, it is important to consider the operating profile of the asset. A discontinuous operation can have consequences on the life of the asset. Starting a machine form standstill in general is paired with higher forces on the bearings. A discontinuous operation would mean these higher forces are applied more frequently. This aspect does play an role in the vacuum compressor pumps but is not that severe. Also, a discontinuous operation does reduce the number of hours the machine is operating.

**Can you say anything about frequent causes related to failure of the vacuum compressor pump?**
A vacuum compressor pump can fail according to multiple aspects. Bu the two most common problems can be categorized as blockage due to the environment and the way the asset is used. Second category is bearing failure. It is advised to monitor these aspects. It is also important to assess why something is failing. Is it the surrounding that is causing the blockage or the way the asset is used. Similar for bearing failure, this can be related to bearing damage due to usage. But can also be the result of unbalance due to impractical practises or the claws that are not aligned and forming higher loads.

**How would you advise to monitor the condition of the asset.**
There are multiple ways the asset can be monitored. The first is measuring the amount of power used by the asset. If the asset is degrading the power required to create the desired vacuum will increase. There are some downsides to this method, difficult to determine what is the problem and where it is located and secondly the damage has to be quite sever will it be able to be detected.
The second option is temperature. The temperature of the pump will be monitored. Higher temperature means a degrading asset. It is important to analyse the temperature since this has effect on the lubrication of the bearings. The lubrication of bearings is very important for the vacuum compressor pumps. Proper lubrication makes a smooth operation possible. When the temperature of the asset increases the lubrication used in the bearings will get thinner. This will result in bearing damage due to the friction that is now possible between the rollers and the walls of the bearing. Temperature will be the monitoring option that is used for a monitoring system Atlas Copco is building into the pump, the SMART Claw. The SMART Claw pump will have two extra temperature sensors used for the monitoring purpose. The final option that is able to detect failure in a earlier stage is vibrations. This is commonly used for bearings. But the data gathered can be harder to analyse.

**Notes Meeting vacuum pump Busch.**
Attendees:
Martin Franssen, Sales support engineer Busch
Laura Mars
Date and Location: 19 September 2021 from 10:00 to 11:00, Online Meeting.
Subject: Failure behaviour of dry claw vacuum compressor pumps.

**Summary:** During the meeting information is provided on the bearings used in the pump.

**General notes:**
In the pump 2 types of bearings are used. The MINK MM 1322 AV asset parts are listed. In the table and the figure provided it became clear that 2 types of bearings are used to rotate the claws. The figure presented has been added to the appendix B.2.

Besides the information on the type of bearings used Martin Franssen also indicated that the bearings inside the pump are in general the bearings that fail. He explains that the load on bearings inside the pump are higher than the load on the bearings which will result in earlier failure of the bearings inside the pump.

The third aspect that is discussed is the maintenance actions that have to be taken when the bearings inside the pump fail. He explains that if the bearings fail the complete pump will be revised. The cost related to this is €3400. This revision takes some time and is in general combined with servicing other parts inside the pump such as the gears.
He also suggest that in some cases it might be more cost-effective to have a pump as spare, this related to the relatively long time that is required to complete the maintenance actions. This aspect is not inside the scope of this research, however should be further analysed by Duyvis.

Beside the standard cost related to the revision he explains that there could also be extra cost related to secondary damage to other parts of the asset. If the bearings are damaged it could result for example in the claws running into the chamber. He estimated the cost related for the secondary damage up to an extra €2000.

Besides the information provided on the bearings we also shortly discussed the failure behaviour of the pump. He confirms that the exact failure distribution of the pump is difficult to determine. This is related to the multiple aspects that influence the life time of the asset. The discusses that the failures can be related to a few standard aspects such as failure due to bad production, bad practise or due to old age.

# D

# Pseudo-code and flow diagram

The first pseudo code is short and compact and the second code can be used if more information is required.

**MACHINE:**

- ➔ Start WORKING()
- ➔ Start PDMProgram()
- ➔ Run Until(SIM_TIME)

**WORKING():**

- ➔ Start = Tsim
- ➔ Select EoL -> random from distribution
- ➔ Run Until: 2 options
  - Tsim = EoL
    - Unexpected Breakdown +1 -> EPM
  - Interrupted by alarm
    - Start maintenance according to alarm code -> EPM, PM, OPM
- ➔ Hold until Maintenance is finished
- ➔ Restart WORKING()

**PDMProgram():**

- ➔ Start = Tpdm
- ➔ Hold(Interval)
- ➔ Determine if machine is ON or OFF
- ➔ If ON:
  - Determine how much life is left in bearing → *BearingLife = (Tpdm + EoL) – env.now*
  - Generate alarm (using alarm and maintenance conditions)
    - AlarmCode = 1,2,3 depending on detection time
  - Tdetection = time alarm generated
- ➔ If OFF:
  - No Data
  - Back to Hold(Interval)
- ➔ Stop PdMProgram() if maintenance is started
- ➔ Restart when WORKING = RESTARTED

**MAINTENANCE():**

- ➔ According to AlarmCode one of the following is activated
- ➔ OPM:
  - Cost = cost maintenance + cost PdM variable
  - Select time to do maintenance → optimum time
  - Select waiting time → Optimum time – detection
  - Hold (waiting time)
- ➔ PM:
  - Cost = cost maintenance + cost PdM variable
  - Hold (planningtime)
- ➔ EPM:
  - Down time hours calculation -> DThour = (detection - EoL) +planningtimeExpress
  - Cost = Cm + Cdt + Cpdm_var
  - Hold (planningtimeExpress)

Figure D.1: Pseudo-Code short

**MACHINE:**

- ➔ Start WORKING()
- ➔ Start PDMProgram()
- ➔ Run Until(SIM_TIME)

**WORKING():**

- ➔ Start = Tsim
- ➔ Select EoL -> random from distribution
- ➔ Run Until: 2 options
  - Tsim = EoL
    - Unexpected Breakdown +1
    - Start EPM
  - Interrupted by alarm
    - Start maintenance according to alarm code:
      - AlarmCode = 1 → Start OPM
      - AlarmCode = 2 → Start PM
      - AlarmCode = 3 → Start EPM
- ➔ Hold until Maintenance is finished
- ➔ Restart WORKING()

**PDMProgram():**

- ➔ Start = Tpdm
- ➔ Hold(Interval)
- ➔ Determine if machine is ON or OFF
- ➔ If ON:
  - Determine how much life is left in bearing → *BearingLife = (Tpdm + EoL) – env.now*
  - Generate alarm (using alarm and maintenance conditions)
    - If: BearingLife >= 0.2 EoL
      - NO ALARM
    - If: 0.1 EoL <= BearingLife < 0.2 EoL
      - GREEN ALARM
        - No AlarmCode
    - If: 0.05 EoL <= BearingLife < 0.1 EoL
      - YELLOW ALARM
      - If #yellow > condition AND #spectrum> 1
        - numAnalysis +1
        - AlarmCode = 1
    - If: 0.01 EoL <= BearingLife < 0.05 EoL
      - ORANGE ALARM
      - If BearingLife < 0.01EoL + planningtime:
        - numAnalysis +1
        - AlarmCode = 3
      - Else:
        - numAnalysis +1
        - AlarmCode = 2
    - If BearingLife < 0.01 EoL
      - RED ALARM
        - numAnalysis +1
        - AlarmCode = 3
  - Tdetection = time alarm generated

- ➔ If OFF:
    - No Data
    - Back to Hold(Interval)
- ➔ Stop PdMProgram() if maintenance is started
- ➔ Restart when WORKING = RESTARTED

**MAINTENANCE():**

- ➔ According to AlarmCode one of the following is activated
- ➔ OPM:
    - # OPM +1
    - Maintenance cost Cm
        - Fixed cost
        - Variable cost from function
        - Bearing cost → random Bearing1 or Bearing2
    - Variable PdM cost Cpdm_var
        - # analysis * Canalysis
        - # inspections * Cinspection
    - Cost = Cm + Cpdm_var
    - Select time to do maintenance → optimum time
    - Select waiting time → Optimum time – detection
    - Hold (waiting time)
- ➔ PM:
    - # PM +1
    - Maintenance cost Cm
        - Fixed cost
        - Variable cost from function
        - Bearing cost → 2(bearing1 + bearing2)
    - Variable PdM cost Cpdm_var
        - # analysis * Canalysis
        - # inspections * Cinspection
    - Cost = Cm + Cpdm_var
    - Hold (planningtime)
- ➔ EPM:
    - # EPM +1
    - Maintenance cost Cm
        - Fixed cost
        - Variable cost from function
        - Bearing cost → 2(bearing1 + bearing2)
        - Express cost
    - DownTime cost Cdt
        - Down time hours calculation -> DThour = (detection - EoL) +planningtimeExpress
            - If DThour > 0:  Cdt = DThour* Cdthour
        - Else: Cdt = 0
    - Variable PdM cost Cpdm_var
        - # analysis * Canalysis
        - # inspections * Cinspection
    - Cost = Cm + Cdt + Cpdm_var
    - Hold (planningtimeExpress)

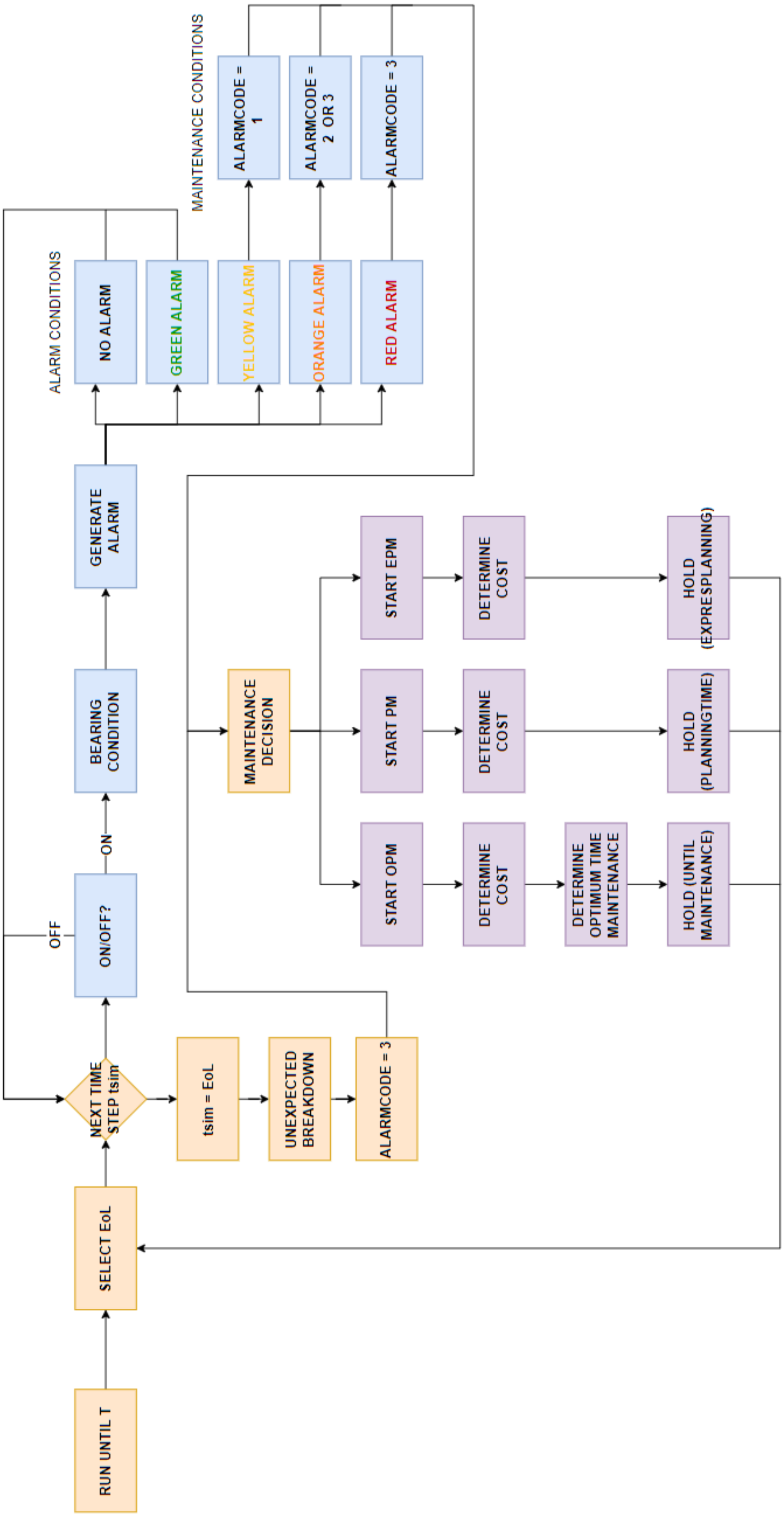



Figure D.2: Flow diagram DES model Large

# E

# Cost input information

As already presented the overall cost is a function of maintenance cost, down-time cost and the cost related to the PdM program. In this appendix more information on these aspects is presented. The cost used in thesis are specific for the case study. To gather the information on the cost aspects knowledge of Jan Droog of Duyvis, Martin Franssen form Busch and Mitch Zonneveld from Facta are used. Also the quotation presented by SKF for the Quick Collect and IMx-1 is used. Same as the quotation from Turck for the banner system.

## Maintenance cost

The first aspect is the maintenance cost. The maintenance cost is a function of a fixed cost, variable cost, bearing cost and express cost if required.

Cost related to the bearings, express and standard revision are presented in an overview provided by Facta. E.1. But beside the cost presented there are some other aspects related to the fixed cost that should be taken into account. Also the variable cost is not taken into account in the information provided by Facta.

### Extra information fixed cost

As already presented the fixed cost consists of the cost related to the standard revision for the vacuum compressor pumps. But an other aspect that should be taken into account is the cost related to the action to be able to perform the maintenance actions, Mitch has also provided information on this subject. First it is important to know that the revision has to take place in the workshop of Facta, which means the pump has to be removed and placed before and after the maintenance actions. This is done by two man for 1 day. They have an hourly wage of €78. Taking the transport into account, of €0.90 per km and the distance from Facta to Duyvis is 13.8 km. Combining this all results in the following overall cost: €4009.68.

### Variable cost

The variable cost is related to the secondary damage that can occur when the damage of the bearing is in a severe stage. Martin Franssen indicates that this is between €600 to €2000, depending on the type of secondary damage and the severity. He also indicates that secondary damage can occur when the bearing is at the end of the third stage. In the simulation model half way through the third stage the variable cost is added but is starting from 0.

## Downtime cost

The downtime cost of an asset is related to the loss in production due to the down time. In the case of the vacuum compressor pump the production capacity is reduced with %60 percent.
Jan Droog indicates the cost for an hour down time as €130. This will be used in the simulation model.

It is important to assess how long the asset is not able to perform its function, resulting in downtime. In the case of an unexpected failure this is related to the time required to plan the maintenance and performing the maintenance.
In the case of detection in the final stage of bearing damage the down time is the planning time required minus the life still left in the bearing. This is added to the time required to perform the maintenance actions.
When the damage is detected in a stage 2 or 3 the down time is only related to the time required for the maintenance actions.
In the simulation only the downtime related to the planning of the maintenance actions, this is due to the aspect that with every detection zone the downtime related to performing the maintenance actions is the same. by removing this it will be easier to run the simulation. But to do this the amount of maintenance actions performed per PdM program should be noted. This will give the ability to calculate the cost related to the down time due to the maintenance actions.

## PdM program cost

The PdM program cost is related to the cost of the investment and the ongoing cost related to the PdM program. This includes the cost for inspections and the cost for analysing the data. The information on the different PdM programs is determined using quotes. In general the quotes are for a larger number of assets, due to this some of the cost had to be divided. below an overview per PdM program on how the cost aspects are determined.

**PdM Program 1: Current situation Facta**
The investment cost for this PdM program is €0, there is no investment needed.
Over 2020 the cost related to the inspections done by Facta where €21000. During the inspection round 195 assets should be analysed per inspection round. In practise this is not always the case, on average 132 of the 195 assets are inspected per round. Dividing the cost over 2020 by 4 gives the cost per inspection: €5250. And dividing this by the assets inspected per inspection round, 132 assets, results in approximately €40 per asset per inspection. This will be used in the simulation model.
Analysing the data gathered during the inspection is part of this price.

**PdM program 2: Quick Collect**
The investment cost for program 2 is a function of the investment cost of the Quick Collect (QC) divided by the number of assets it will be used for. The investment cost for a QC is €4530. This is a function of the initial investment cost of €1890 and 4 times the licence cost resulting in €2640. This cost will be divided over the 195 assets. This result in an investment cost of €24 per asset.
The data will initially be analysed in-house, but in the case of an alarm the data will be analysed by the experts at Facta to analyse the data in more depth. The cost for analysing the data is €53.
The inspection will be performed by in-house personnel. Due to this there are no extra cost taken into account for this aspect. But it is important to notice that the activities of in-house personnel will change due to the introduction of the QC.
It is expected that the time needed to gather the data per asset is 10 minutes.

**PdM program 3: IMx-1**
The IMx-1 is an online monitoring application from SKF that consists of an wireless sensor, a gateway and a router for the gateway. The different aspects of the program all come with their own cost. Respectively, €262.50, €1260 and €800. Sometimes a part of an program can be used by multiple assets. In the case of the IMx application the distance between the sensor and the gateway is only a few meters. The vacuum compressor pumps, all four, are placed in one room. Due to this the cost related to the gateway and the router will be divided by 4. The sensor is only able the measure in one direction and it is advised to place three sensors per asset. This means the cost for the sensor is multiplied by three. This all results in an investment cost per asset of: €
The sensor will be collecting the data resulting in zero cost and the cost related to the analysis of the data is the same as for PdM program 2, only €53 when the data has to be analysed by the experts at Facta due to an alarm.

| Imx cost | per piece | quantity | Used by # assets | total |
|---|---|---|---|---|
| gateway | 1260 | 1 | 4 | 315 |
| sensor | 262.5 | 3 | 1 | 787.5 |
| router | 800 | 1 | 4 | 200 |
| Total Investment Imx | | | | **1302.5** |

**PdM program4: Banner**
The Banner application also consists of multiple parts, the sensor is in this application connected with a wire to a radio which transfers the data to the gateway. Due to this the following parts are required: sensor (€231.60), radio (494.40), battery for radio (€44.40), cable (€54.45), gateway (€619.20), router (€291.60) and the mounting bracket (€48)
The range between the radio and the gateway can be longer than with the IMx, due to this the gateway will also be able to be connected with mixomats which are on the other side of a wall. Due to this the cost for the gateway, router and mounting bracket will be divided by 8. The advise from Banner is to use 2 sensors per asset due to the two direction measurements. The cable used is able to connect 4 sensors to one radio. Due to this the radio, with battery and cable will be used to apply the application to 2 assets., the cost for these parts will be halved to get the cost per asset. Using this information the total cost for the investment is €931.05. Although this is the cost for the investment it is important to add the cost for the batteries that have to be replaced after a years. Resulting in a cost of €997.65 over 4 years.
The cost for the analysis and the inspection are the same as for the IMx.

| banner cost | per piece | quantity | Used by # assets | total |
|---|---|---|---|---|
| gateway | 619.2 | 1 | 8 | 77.4 |
| sensor | 231.6 | 2 | 1 | 463.2 |
| batterij | 44.4 | 1 | 2 | 22.2 |
| kabel | 54.45 | 1 | 2 | 27.225 |
| radio | 494.4 | 1 | 2 | 247.2 |
| Router | 291.6 | 1 | 8 | 36.45 |
| montage | 48 | 1 | 8 | 6 |
| Total Investment Banner | | | | **879.675** |

**PdM program 5: Combination, Quick Collect and Banner**
In program 5 the investment cost will be the sum of the cost for the banner application with the Quick Collect. Due to this the investment cost for PdM program 5 is: €1025.65.
The inspection cost will be zero again and the cost related for the analysis performed by Facta is €53.

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***Aangevraagd door:***
Duyvis Production BV
T.a.v. mevr. Mars
Diederik Sonoyweg 17
1509 BR Zaandam

# Offerte

Behandeld door : Mitch Zonneveld
Uw referentie : BUSCH Vaccuumpomp

**Offerte nr. : UG- 12110491**
Offertedatum : 20-10-2021

Geachte mevrouw Mars,

Wij danken u voor uw aanvraag en hebben het genoegen het volgende voorstel vrijblijvend aan u voor te leggen.

| Aantal | Omschrijving | Prijs per stuk € | Totaal-prijs € |
|---|---|---|---|
| | **Standaard revisie** | | |
| 1,00 | Standaard revisie vacuumpomp Busch MINK MM1322 incl. motor:<br>- Ingangscontrole<br>- Reinigen van onderdelen met hogedruk-heet waterreiniger<br>- Mechanische tolerantiemetingen<br>- Dynamisch balanceren as bezetting<br>- Vernieuwen van de asafdichting en de lagers<br>- Afpersen pomp met water en/of lucht<br>- Uitwendig conserveren | 1.464,00 | 1.464,00 |
| 2,00 | LAGER 3309 A/C3 | 122,05 | 244,11 |
| 2,00 | SKF NU 208 ECP/C3 | 47,74 | 95,48 |
| 1,00 | Expresse levering lagers binnen 24u indien voorradig NL | 150,00 | 150,00 |

Prijzen : netto in EURO, per stuk, excl. 21% BTW
Leveringsconditie : Ex Works - Af fabriek
Betaalconditie : binnen 30 dagen *(tenzij anders overeen gekomen)*
Prijsopgave / Offerte : geldig t/m 30 dagen na dagtekening
Onderzoekskosten : Indien u geen gebruik maakt van onze offerte zullen wij eventuele onderzoekskosten in rekening brengen.

**Totaalbedrag excl. BTW € 1.953,59**

Wij streven ernaar de door u gewenste leverdatum te realiseren maar vragen uw begrip voor het feit dat alle door ons bevestigde levertijden afhangen van juiste en tijdige bevoorrading van onze leveranciers.
Op al onze offertes, op alle opdrachten aan ons en op alle met ons gesloten overeenkomsten zijn de METAALUNIEVOORWAARDEN 2019 van toepassing.
Deze voorwaarden zijn gedeponeerd bij de griffie van de rechtbank Rotterdam en kunt u downloaden op onze website www.facta.nl.
De toepasselijkheid van uw algemene (inkoop)voorwaarden wordt uitdrukkelijk van de hand gewezen.

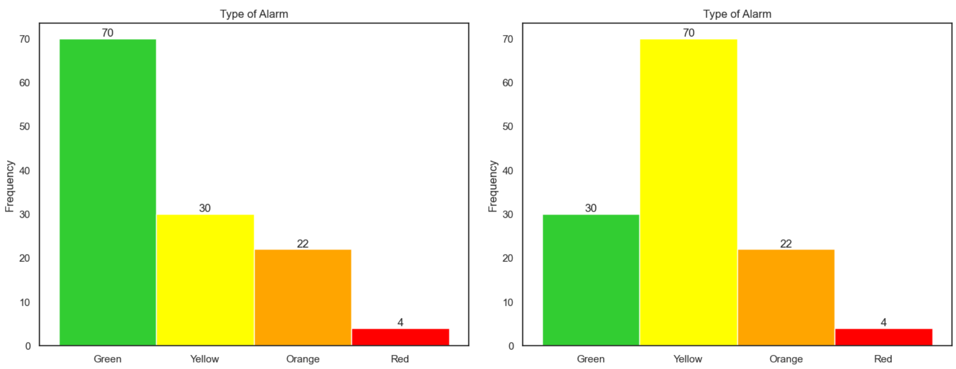
Figure E.1: Cost overview Facta

# F

# Verification Data

In this appendix the information used to verify the model is presented. 5 different test where used to verify the model.

**Test 1: Switching alarm conditions**
In this test the alarm conditions for a green and a yellow alarm are switched. In fig F.1a the number of alarms are presented. In figure F.1b the number of alarms generated after changing the conditions are presented. In the figure it can be seen that the number of green alarms before is the number of yellow alarms after changing the conditions.




(a) Original results

(b) After changing results

Figure F.1: Results test 1 verification

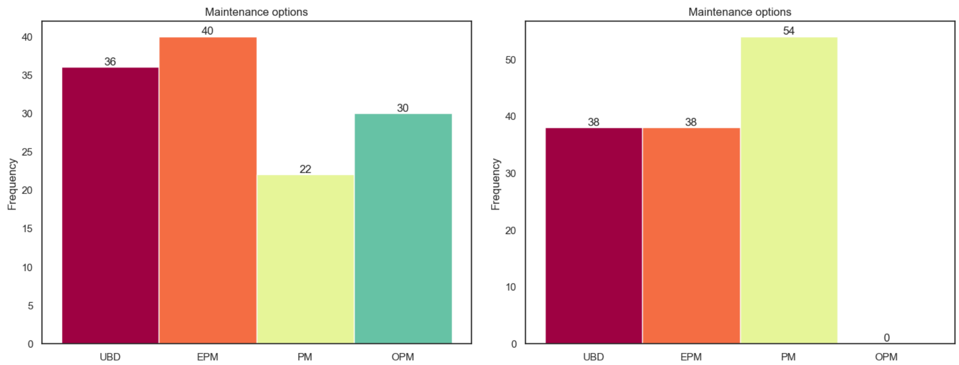
**Test 2: Increasing the fixed maintenance cost**
In this test the fixed cost used to determine the maintenance cost is multiplied by two. It is expected that the overall cost will increase as well, related to the number of maintenance actions. This test is done to check if the number of maintenance and cost aspects are correctly taken into account.
The overall cost of all the repetitions over 4 years for the original case is: €725953
The overall cost of all the repetitions over 4 years for the changed case is: €1092789

**Test 3: Changing the percentage ON**
Test 2 is used to assess if the condition of the machine is incorporated correctly. The percentage ON, used to simulate the frequency the asset is ON, is in the original case 1, 100 percent. The percentage will be changed to 0.5, 50 percent, to assess the number of No Data. It is expected this is zero for the original case and increases in the changed situation. The result of this test is presented in table F.1

| type of alarm | Original | After |
|---|---|---|
| No Data | 0 | 400 |
| No Alarm | 595 | 295 |
| Green | 70 | 28 |
| Yellow | 30 | 9 |
| Orange | 22 | 5 |
| Red | 4 | 2 |

Table F.1: Data alarms generated in test 2

**Test 4: Alarm code altering**
In test 3 the alarm codes generated by the PdM program are always 2. Normally the alarm code depends on the detection zone and the alarm generated, yellow, orange or red. In the test the alarm codes are always 2. It is expected that this will result in an increase in the number of PM, which is coupled to alarm code 2. The number of OPM will be zero and the number of EPM will be equal to the number of unexpected breakdowns. Unexpected breakdowns always activate the EPM strategy. The results of this test are presented in figure F.2 where the original case is F.2a and the results after the changes are presented in F.2b.




(a) Original results (b) After changing results

Figure F.2: Results test 3 verification

**Test 5: Checking the cost related to down time**
In this test the cost related to down time is checked by calculating the cost and checking if the model has the same result.
In the case of an unexpected breakdown the hours downtime will be 2, related to the express planning time. Multiplying this by the hour cost for the down time, €130, results in: €6240.
In the simulation model an end of life time of 353 days results in an unexpected breakdown. The cost related to down time for this EoL is €6240.

# G

# Sensitivity analysis

In this appendix the results of the sensitivity analysis are included for the reliability. In the research only the results of the sensitivity analysis related to the overall cost is presented. In the figure the following parameters are presented.

| # | Parameter | Base case | Lower value | Higher value |
|---|---|---|---|---|
| 1 | Planning time | 14 days | 3 days | 21 days |
| 2 | Express planning time | 2 days | 0 days | 7 days |
| 3 | Simulation time | 4 years | 2 years | 8 years |
| 4 | Starting point variable cost | 3 weeks | 1 week | 5 months |
| 5 | Number of data points required (X) | 10 | 1 | 25 |
| 6 | Likeliness infant mortality | 0.05 | 0.01 | 0.15 |
| 7 | Likeliness usage failure | 0.6 | 0.45 | 0.75 |
| 8 | Likeliness wear out | 0.35 | 0.2 | 0.5 |

Table G.1: Parameters for the sensitivity analysis

The results are similar as the results discussed in the research.

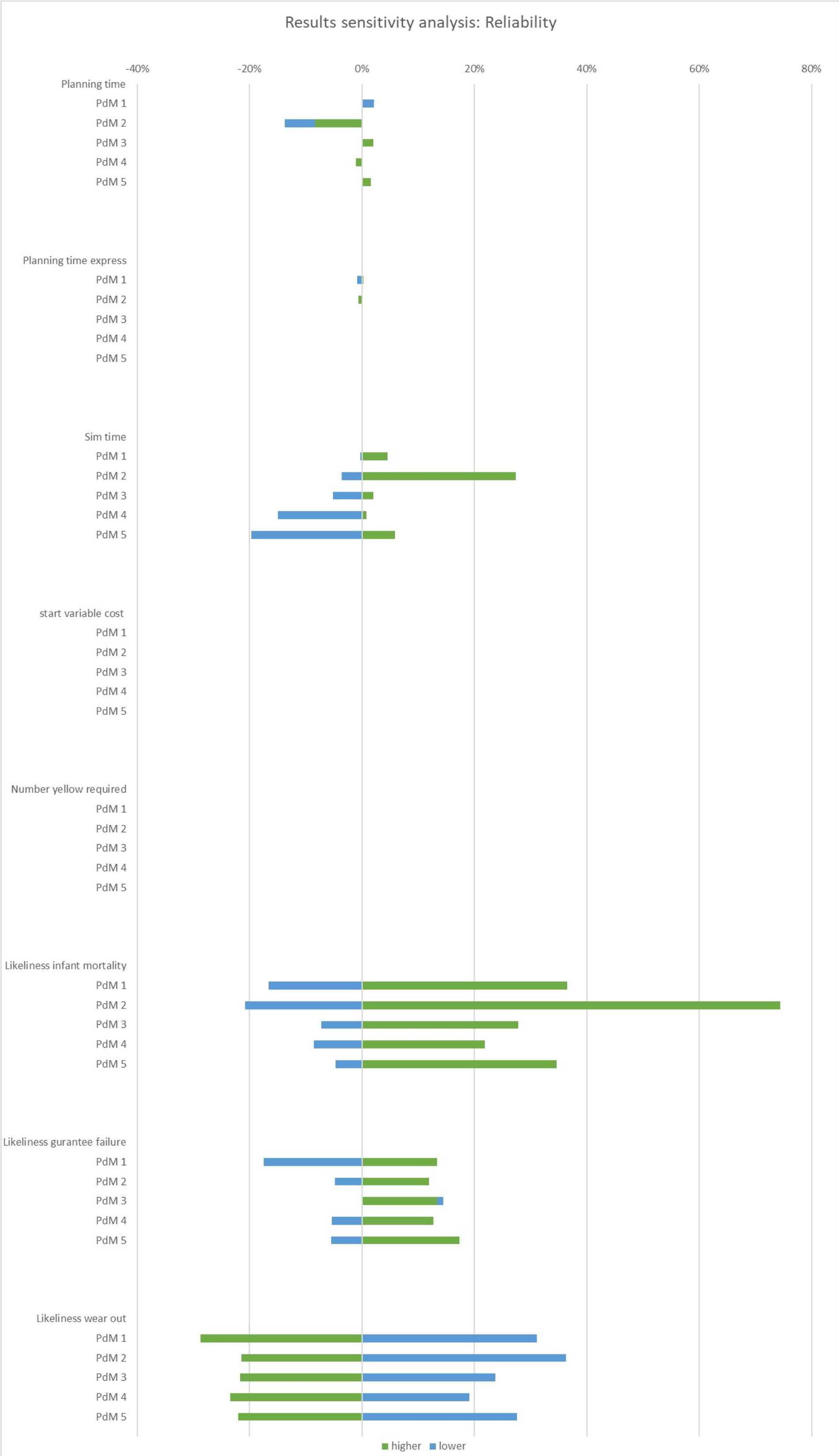



Figure G.1: Sensitivity result Reliability

# H Results

In this appendix the all the graphs on the overall cost and the reliabilty gathered by conducting the tests are presented.

## H.1. Test 1: Alarm conditions

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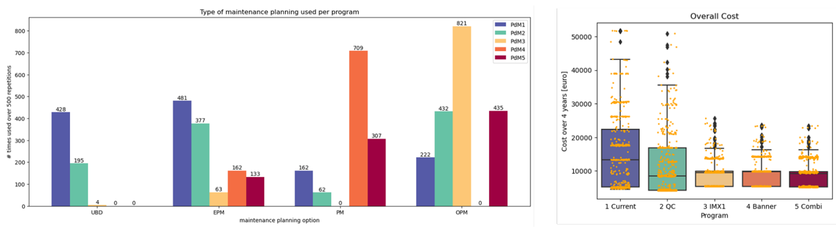
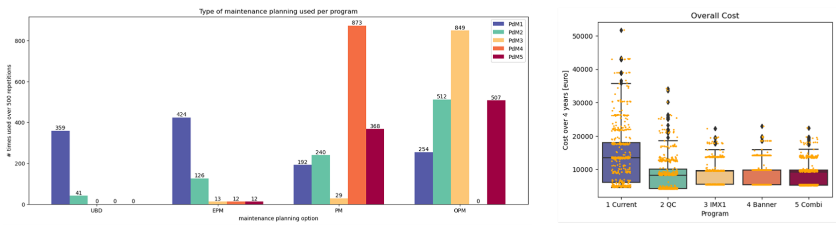


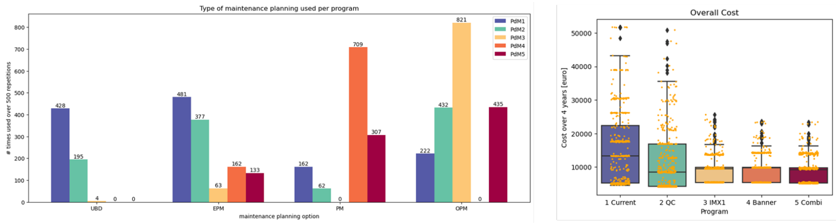

(a) Literature based alarm conditions



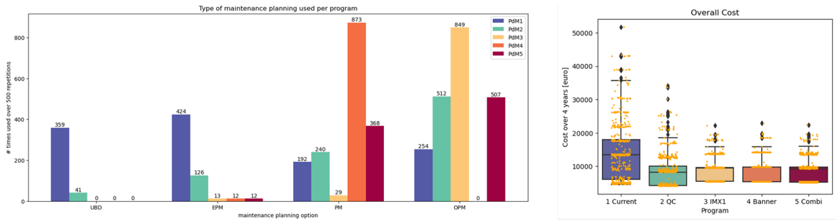

(b) Practice based alarm conditions

## H.2. Test 2: Failure distribution

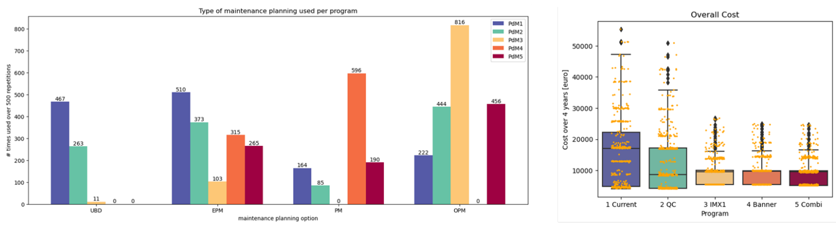
1. **General:** Distribution based on the inofmraiton provided by Atlas Copco
2. **Random Failure:** Due to the high levels of uncertainty related to the failure behaviour of the pump, it could be said that the failure distribution is random.
3. **Wear Out:** The probability that the asset will fail will increase with time. Related to old age.
4. **Bathtub:** A combination of infant mortality with wear out damage.
5. **Short:** The asset will fail either to infant mortality or due to bad practice related to the guarantee period.
6. **Partially failure:** The standard failure distribution, but the distribution is now spread over 10 years.
7. **No failure:** The asset will not fail within the simulation period



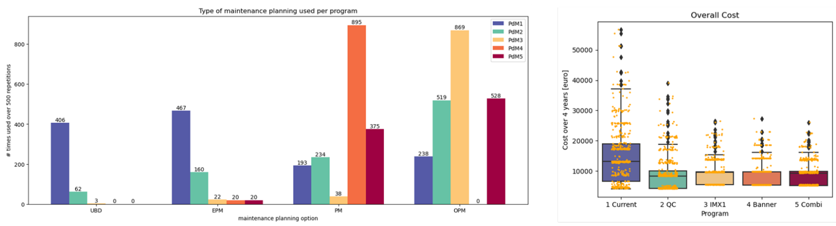

(a) General literature



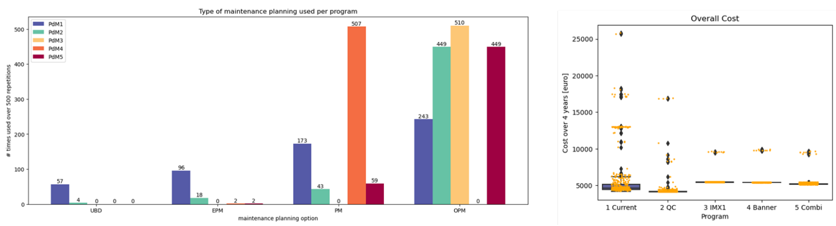

(b) General practice



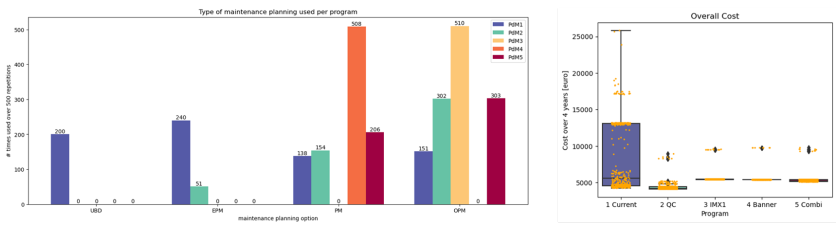

(a) Random literature



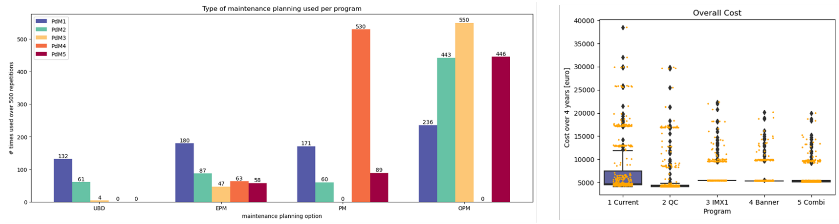

(b) Random practice



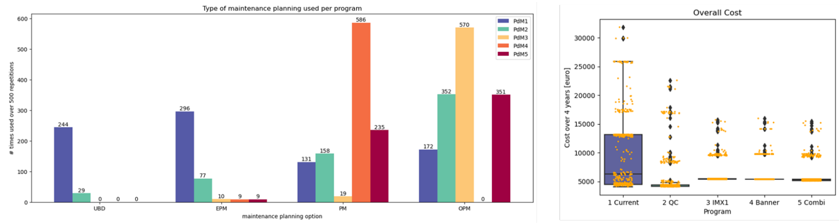

(a) Wear out literature



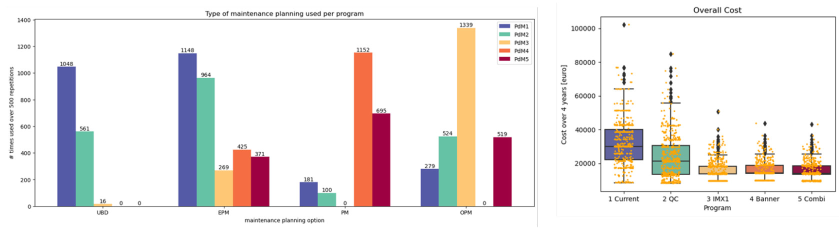

(b) Wear out practice



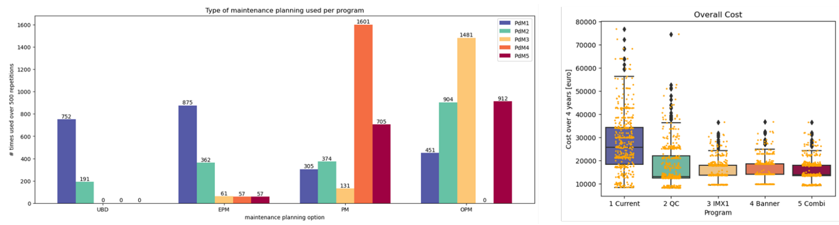

(a) Bathtub literature



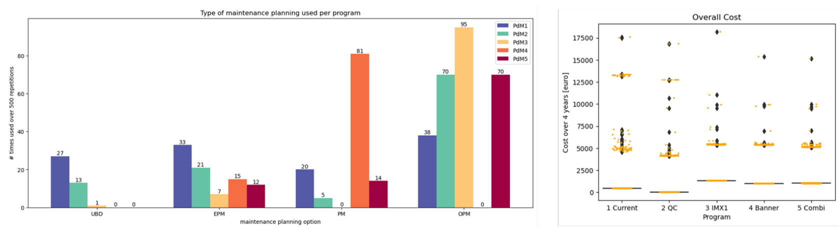

(b) Bathtub practice



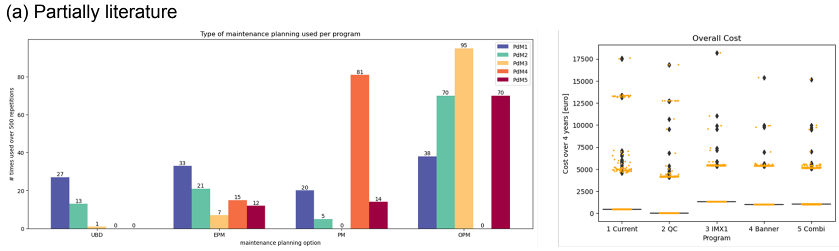

(a) Short literature




(b) Short practice



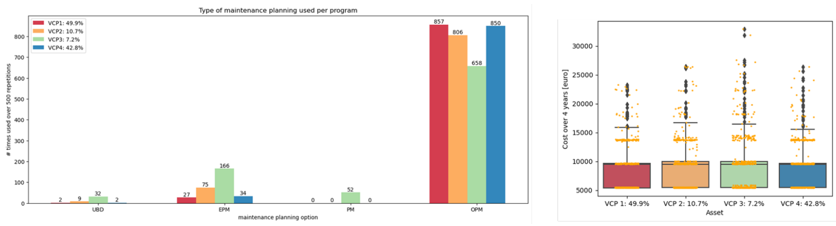

(a) Partially literature



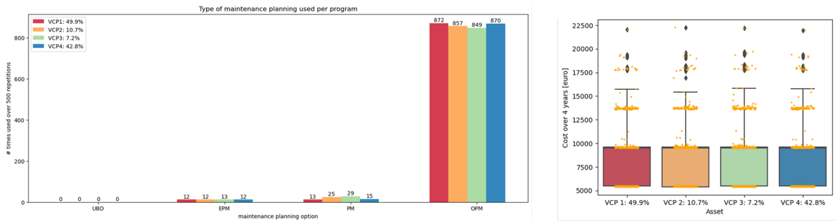

(b) Partially practice

## H.3. Test 3: ON/OFF ratio

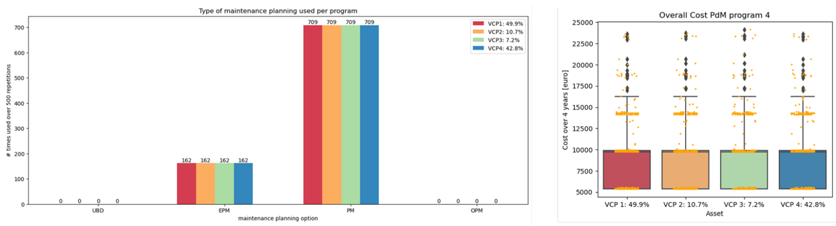
The results of the analysis of the ON/OFF ratios.



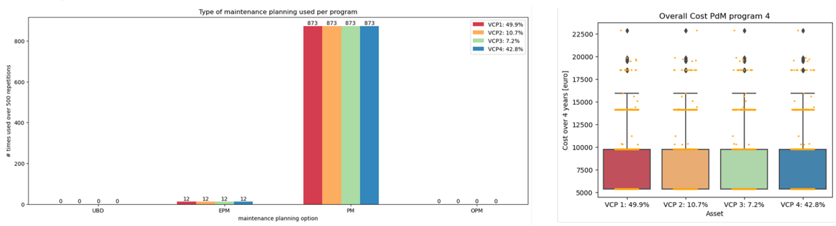

(a) program 3 literature



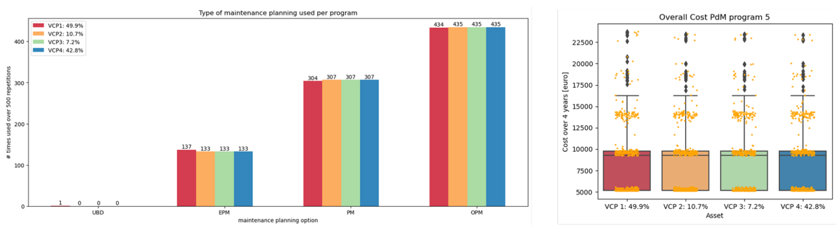

(b) Program 3 practice



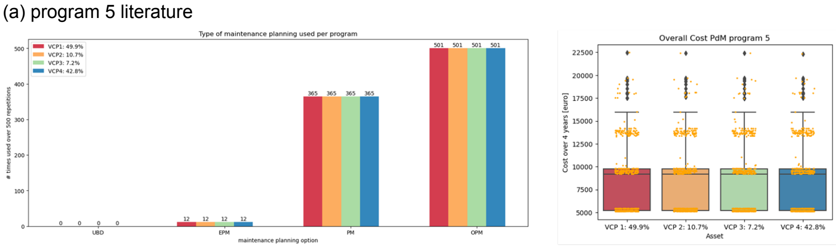

(a) program 4 literature




(b) Program 4 practice



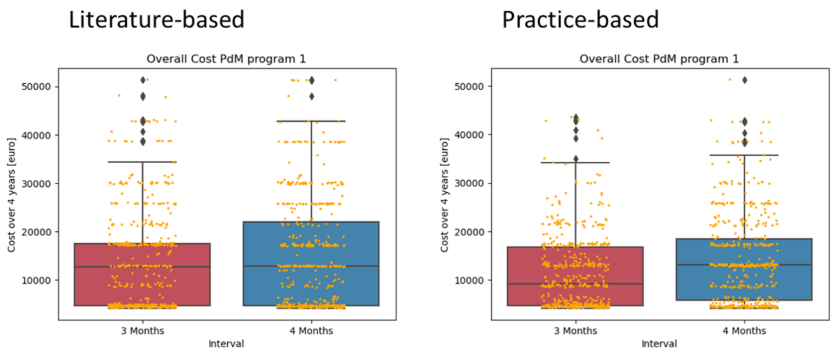

(a) program 5 literature



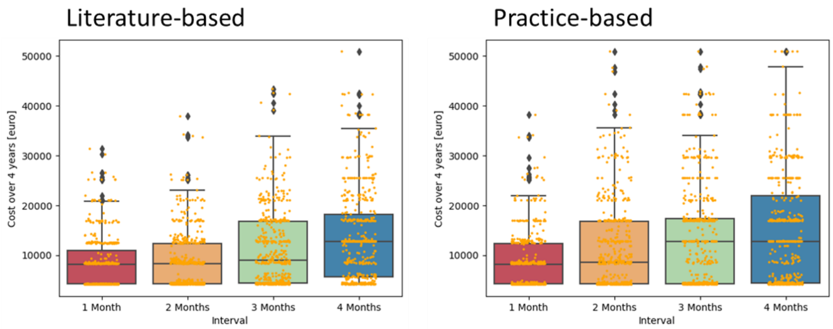

(b) Program 5 practice

## H.4. Test 4: inspection interval

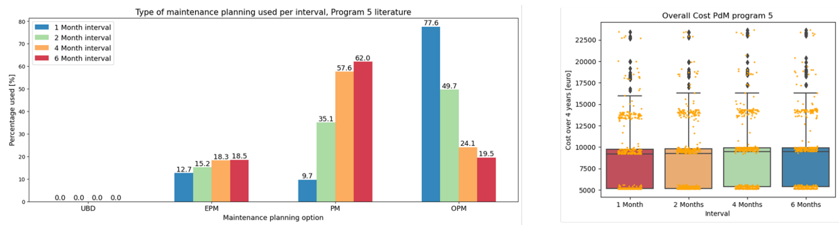
For test 4 only the overall cost related to program 1 and 2 are generated. This provided enough information to gain insight in the effect.



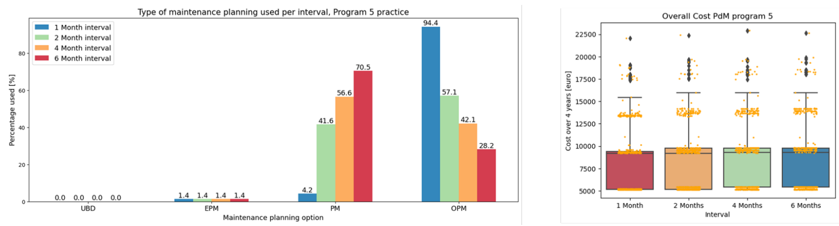

(a) Overall cost program 1




(b) Overall cost program 2




(a) Interval program 5 literature




(b) Interval program 5 practice