Predictive maintenance on bridges

Final Report

Design Project

MSc Mechanical Engineering (Smart factories)

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Abstract

Predictive maintenance on bridges

This design project took place at the company Beenen Industrial Automation. Beenen designs and realizes complete control systems for the industrial, infrastructure, and water technology sectors. Besides this, they are also responsible for the maintenance services on the bridges and locks in the Province Overijssel and provide 24-hour maintenance support in all sectors. Beenen wants to investigate whether the maintenance on the bridges can be performed 'smarter' by utilizing different maintenance strategies alongside Corrective Maintenance, which is currently used. Corrective Maintenance has the goal to identify the failure or error and rectify it to make the asset operational again. The disadvantage of performing Corrective Maintenance is that failures are normally detected when it is already too late to take preventive measures. Alternative maintenance strategies will be discussed and a Decision Making Grid is used to assign the correct maintenance strategy to different parts of the bridges. For example, Condition-based Maintenance is advised for the maintenance of the mechanical parts of the bridges, while Preventive Maintenance is advised for the maintenance of the cameras. The Condition-based Maintenance strategy is further examined by setting up a pilot project using vibration analysis to perform Condition-based Maintenance on a bridge located in Giethoorn Noord. During this pilot, an anomaly was detected which could indicate an upcoming bearing problem in the electrical motor of the bridge. In the future, both the condition monitoring system, as well as the other maintenance strategies can help Beenen to perform maintenance before a malfunction occurs and minimize the downtime.

Contents

List of Abbreviations

CM	Corrective Maintenance
PvM	Preventive Maintenance
CBM	Condition-based Maintenance
PdM	Predictive Maintenance
TBM	Time-based maintenance
DMG	Decision Making Grid
CMMS	Computer Maintenance Management System
OTF	Operate to Failure
SLU	Skill Level Upgrade
DOM	Design out Maintenance
BPFO	Ball passing frequency outer race
BPFI	Ball passing frequency inner race
BFF	Ball fault frequency
FTF	Fundamental train frequency
PLC	Programmable logic controller
MDR	Motor driven end
RMS	Root Mean Square

Chapter 1: Introduction

The proper functioning of movable bridges allows people and goods to travel on roads and waterways. Bridges are important for transport in the Netherlands. Almost everyone passes one or more bridges every day. This is not surprising when you consider that there are thousands of bridges in the Netherlands, including 1500 movable bridges. The advantage of movable bridges is the high vertical clearance for boat traffic. The downside is that the repetitive opening and closing movements will lead to deterioration of the mechanical and electrical system of the bridge. This alongside the complex integration of the mechanical, electrical and structural components will lead to more malfunction relative to fixed bridges. The 32 moveable bridges that Beenen oversees already have around 250 malfunctions per year. These malfunctions can hamper the operation of a movable bridge, and hence its serviceability can be disrupted or completely compromised. The maintenance cost is also higher for movable bridges compared to fixed bridges due to the complex integration of the different components [Catbas et al., 2013]. For these reasons, it is especially important for movable bridges that maintenance is carried out properly to keep the number of malfunctions as low as possible.

Chapter 2: Maintenance strategies

Many different maintenance strategies could be useful for the maintenance of a bridge. The main strategies that will be discussed in this report are Corrective Maintenance (CM), Preventive Maintenance (PvM), Condition-based Maintenance (CBM), Predictive Maintenance (PdM), skill level upgrade (SLU) and Design-out Maintenance (DOM). However, which strategy can be best implemented depends upon the system or even subsystem of your asset [Aslam-Zainudeen and Labib, 2011].

CM or ‘Run-to-failure’, has the goal to identify the failure or error and rectify it to make the asset operational again. For non-critical assets, CM is considered a reasonable operating strategy because the cost is generally low. This is because it can be performed with a fewer number of resources and maintenance infrastructure [Deighton, 2016, Neelamkavil, 2010]. The disadvantage of only using CM is that it is inefficient and in the long term can be very expensive because failures are normally detected when it is already too late to take preventive measures. This can lead to more damage to the assets which can again lead to longer repair times. Also, the root cause of the failure will not be determined since the goal is to rectify the failure and ensure that the asset is operational again, not to determine the root cause. This will lead to many repeat failures which will further increase the maintenance costs.

PvM (sometimes called time-based or periodic maintenance), performs maintenance tasks at set time intervals. The goal of preventive maintenance is to carry out the maintenance before a failure occurs. For many critical assets, preventive maintenance can help eliminate failures. The disadvantage is that because the maintenance activities are performed ahead of time and are performed regardless of whether signs of deterioration are prevalent or not there is a risk of performing unnecessary maintenance. This will of course increase the cost [Neelamkavil, 2010].

CBM, the condition of the asset is being monitored continuously and an alert is given when a pre-established threshold is reached. In this way, the maintenance can be applied in time and avoid a failure [Neelamkavil, 2010]. However, to reach the higher levels in the maintenance maturity matrix more investments are necessary for sensors, data management and equipment [Ahmad and Kamaruddin, 2012, Newton, 2018].

PdM, is an improvement on CBM and relies on statistical methods, such as machine learning, to dynamically define when a machine is performing as intended or needs maintenance. The more data sources and data available, the better the predictions. One of the biggest disadvantages of predictive maintenance is the necessary high investment costs. The already high cost that comes with implementing a CBM strategy is needed and on top of that staff members that can interpret the data with the help of artificial intelligence techniques are needed to achieve true predictive maintenance [Carvalho et al., 2019].

SLU, can be used when breakdowns occur often but can also be fixed quickly. Minor tasks such as the resetting of the controls can be solved fast by improving the skills of the staff by giving training courses or by using a comprehensive manual [Seecharan et al., 2018].

DOM, is a strategy where the asset is redesigned to remove the failure cause. This strategy can be applied when an asset is considered not fit for purpose [Seecharan et al., 2018]. However, sometimes it is impossible or expensive to redesign an asset to design out maintenance. In this case, the asset should be designed for effective and efficient maintenance [Markeset and Kumar, 2003].

Chapter 3: Problem analysis

3.1 Current state

In the current situation, action is taken when a notification is received that one of the bridges or locks is not working properly. This is the CM strategy that was discussed in the previous chapter. Because of this strategy, Beenen often runs into the same malfunctions. When there is a malfunction, the most important thing is that the bridge becomes operational again. As a result, there is often no time to find out the exact reason for the malfunction.

3.2 Problem description

Due to the CM strategy, a lot of call ups are needed to make an asset operational again whenever a malfunction occurs. As a first step, it can be interesting to see when these malfunctions occur. In the top part of figure 1, the amount of malfunction during a period of around two years is shown. It can be seen that in July and August there are more malfunctions than during the rest of the year due to the boating season. There are also less busy periods which means that if maintenance can be performed in advance it can be scheduled in a period when fewer malfunctions occur. In the bottom part of figure 1, the malfunctions per day are shown. It is fairly evenly distributed, only on weekends and especially on Sundays there are fewer reports, while on Monday there are a bit more compared to the other weekdays. This may be due to the way the failures are reported. During working hours, the bridge operator calls the supervisor who must then determine whether a service engineer should go to the location. Outside normal working hours and on weekends, the bridge operator will call the breakdown service directly if there is an emergency. Furthermore, the bridges do not run on Sundays outside the boating season which runs from the first of April until the first of November. In figure 2, the number of malfunctions that occurred per day is shown in a Pareto plot. From this plot, it can be seen that in 50% of the days no malfunction appears, which indicates the room to perform predictive maintenance. The need for a different maintenance strategy is further supported by the fact that in 25% of the days there are two or more malfunctions as can be seen in figure 2. This could lead to longer downtimes, because of the limited availability of service engineers.

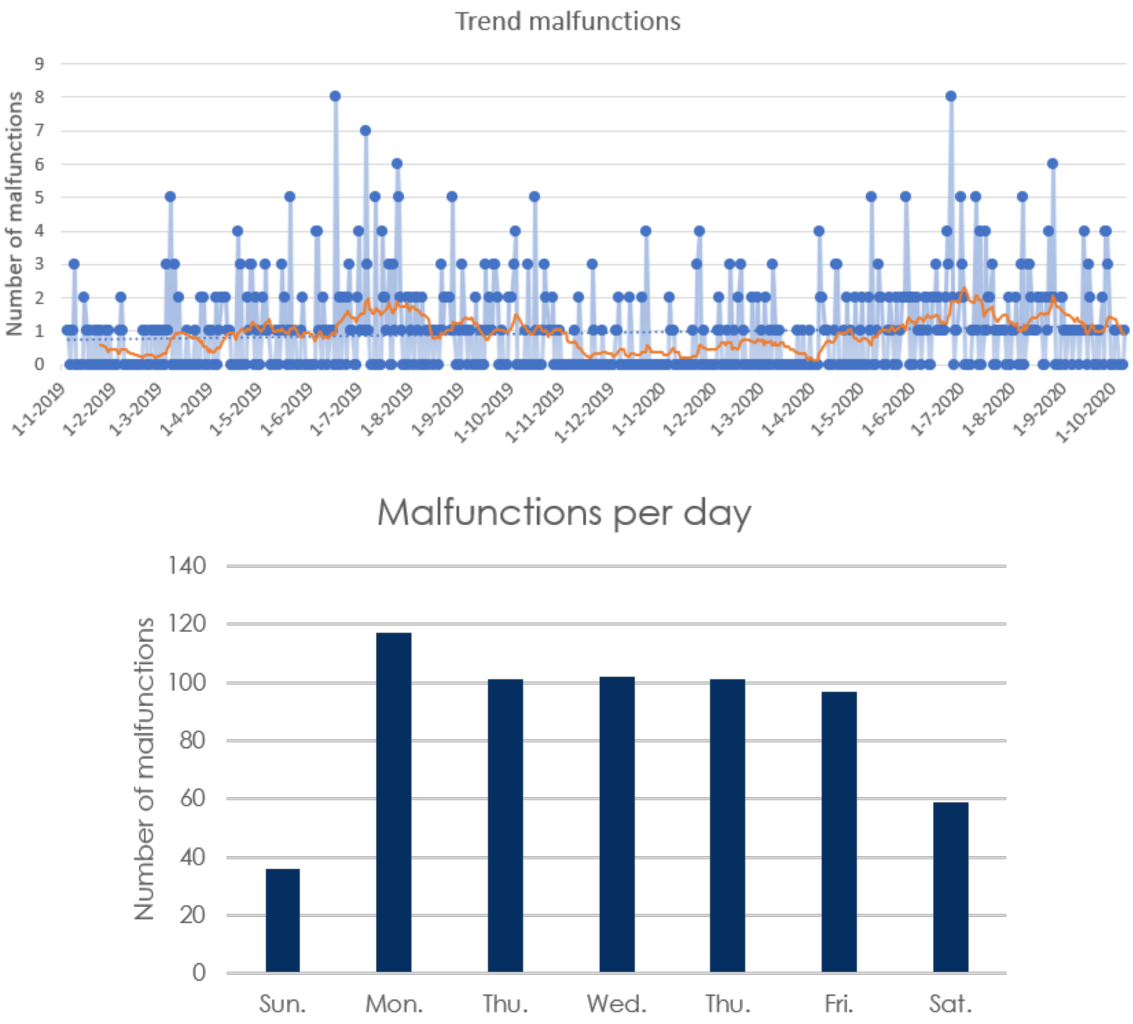

Figure 1: The top figure illustrated the number of malfunctions during a period of around two years. On the x-axis, the timeline is shown, and on the y-axis, the number of errors is shown. The bottom figure depicts the number of malfunctions per day of the week. On the x-axis, the days of the week are placed while on the y-axis the total number of malfunctions that occurred on the day during the period of two years is depicted

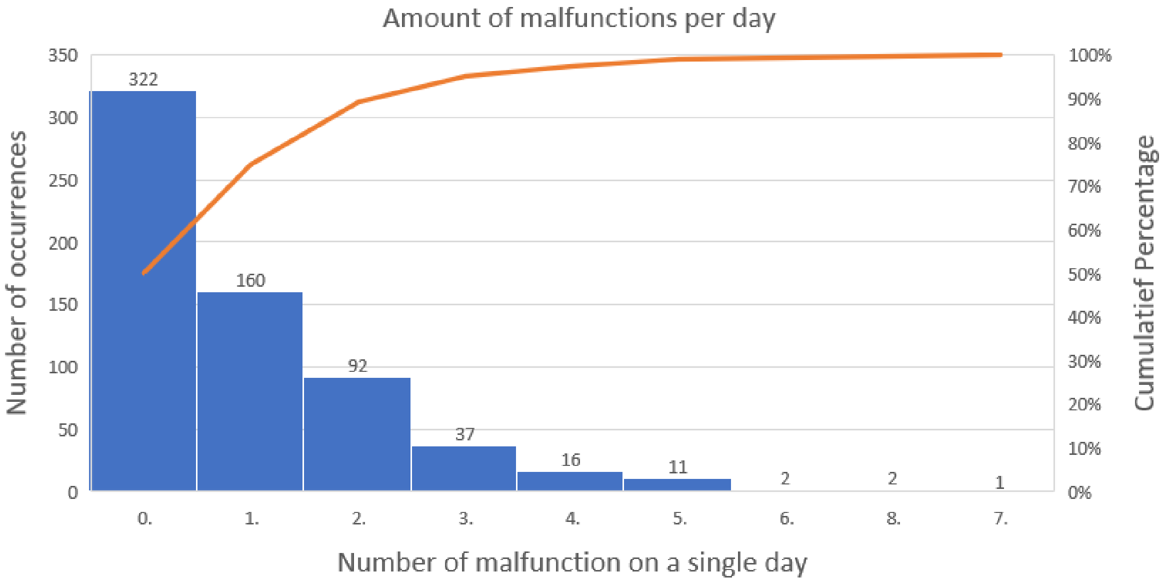

Figure 2: The figure depicts how often a certain number of malfunctions occur in one day. On the x-axis, the number of malfunctions that occurred on the same day is shown, while on the y-axis the number of times this happened can be read. So on 322, days no malfunction occurred while on 160 days a single malfunction was reported. The data is from the same two years and includes the data of all 32 bridges.

3.3 Stake-holder analysis

There are five main stakeholders in this project:

- **Beenen**: The company has a service contract with the Province of Overijssel and wants to extend this for the coming years. By improving the maintenance strategy the number of malfunctions and resulting downtime can be reduced. This will result in fewer visits to the assets to perform maintenance which saves costs and helps to keep the assets operational. By exploring new maintenance techniques such as Condition-based Maintenance it shows the province that Beenen is willing to make investments to improve the maintenance of the bridges and locks.
- **Province of Overijssel**: The province of Overijssel is responsible for the provincial waterways. The province benefits from little disruption to the assets. They want as few obstructions as possible and want traffic in the province to flow smoothly without disruptions and therefore want to remain involved during this project and the pilot.

- **Suppliers**: For the CBM system industrial equipment is needed. If the pilot is proven successful it can be implemented on other assets. This is why the suppliers are also interested in the results of the pilot to see if a more extensive cooperation is possible in the future. The suppliers hope to generate more income in this way.
- **Commercial transport**: Companies that transport goods within the province want as little disruption as possible. If a vessel or a truck is unable to transport its goods due to a malfunction at a bridge, this can result in a lot of extra costs. In this category, you can also place other transport that has a high interest in a bridge that always works, such as the police.
- **Recreational transport**: Even though the consequences of a breakdown for recreational transport are less than for commercial transport, they also want as little disruption as possible.

The stakeholder can be placed in a power/interest grid which can determine the actions needed to align their goals with the project. The matrix is shown in figure 3.

3.4 Scope

During this project, a wide analysis of the possibilities of implementing different maintenance strategies is performed. This is done by analyzing historic data and look at which maintenance strategy can be best applied to a specific part of a bridge. Literature research is performed to determine the benefits and disadvantages of each maintenance strategy. At first, the plan was to optimize the maintenance strategy for both bridges and locks but because of the limited time, only the maintenance on bridges will be examined.

In the second part, one maintenance strategy is explored in more detail, CBM. This is because CBM is often seen as the maintenance strategy of the future, which is why the company is interested in investigating the possibilities of CBM. The testing of the CBM strategy will be limited to one pilot bridge. At first, the plan was to test on multiply bridges and a lock but due to corona the allowed physical presence at both the company and at the bridges was limited. As a result, it was decided to first test the CBM strategy on only one bridge.

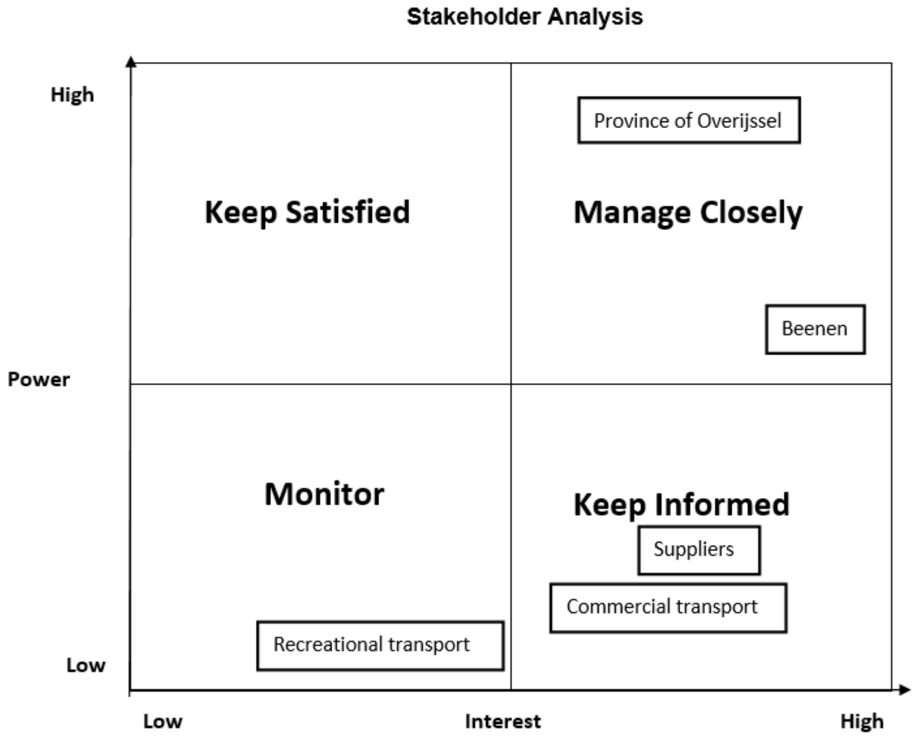

Figure 3: Beenen is the stakeholder with the most interest in the project, while the province has the highest power. Both the suppliers and commercial transport have an interest in the project but do not have power over it. Recreational transport has the least interest and power of all the stakeholders.

Chapter 4: Research objectives & Structures

4.1 Goal

Beenen is currently using CM on the bridges in the province of Overijssel. Due to a high amount of malfunctions and the inefficient way the maintenance is currently performed unnecessary costs are incurred, downtime is longer than it needs to be and repeat failures are not resolved. Based on the current state the goal of this design project is the following:

Design a smarter maintenance strategy for the bridges, to decrease the cost and/or increase the reliability.

No specific maintenance strategy should be implemented. However, Beenen is interested in exploring the possibilities of CBM.

4.2 Research question

Now that the goal of the research is clear and the main problems are discussed, the research question can be formulated. The main research question becomes:

- Which maintenance strategy that can be found in literature is most cost-effective/results in the highest reliability?

Although the above question defines the main question that should be answered, it does not cover all the important questions that should be answered. To obtain more structured research, some sub-questions are formulated:

- Which alternative maintenance strategies are available?
- Which strategy should be implemented, and should different strategies be implemented for different parts of a bridge?
- Which CBM technique should be implemented, and which variables are to be measured?
- How should the CBM system be designed to improve reliability by monitoring the current condition of the asset?

4.3 Methods

4.3.1 Cycles of Hevner

From the three cycles described by Hevner (Figure 4), the project makes use of all three cycles. The Rigor Cycle provides grounding theories and methods along with domain experience and expertise from the foundations of the knowledge base into the research and adds the new knowledge generated by the research to the growing knowledge base. Additions to the knowledge base as results of design science research will include any extensions to the original theories and methods made during the research, the new meta-artefacts, and all experience gained from performing the research and field testing the artefact in the application environment [Hevner, 2007]. In this design project, a pilot will be set up that used CBM to monitor the condition of a bridge. This monitoring solution will be field-tested and can later be used for similar applications.

The relevance cycle provides the requirements of the research, so these are the opportunities and the goals for the research. These requirements come from the application domain which are the people, organizational systems and technical systems that together work towards a goal. The pilot project is later field-tested to determine if additional iterations of the relevance cycle are necessary. If the design does not work in the practical environment another iteration will commence but now with the feedback from the field test and restated requirements to improve the design. During the project, different CBM setups were deployed on the bridge before a design was obtained that was practical in the real world.

The design cycle is located between the relevance cycle and the rigor cycle. The inputs for this cycle are the requirements from the relevance cycle and the theories and methods from the rigor cycle. The cycle consists of the construction and the evaluation of the design artefact and iterates more rapidly compared to the other cycles. A design is first evaluated in the design cycle and if it is deemed sufficient it moves on to the field testing in the relevance cycle. The coding and parameter selection of the different sensors is for example something that had to go through multiple iterations before it could move on to the relevance cycle.

4.3.2 Data sources

- Historic data: The data from previous malfunctions is needed to see what other maintenance strategies can be applied.

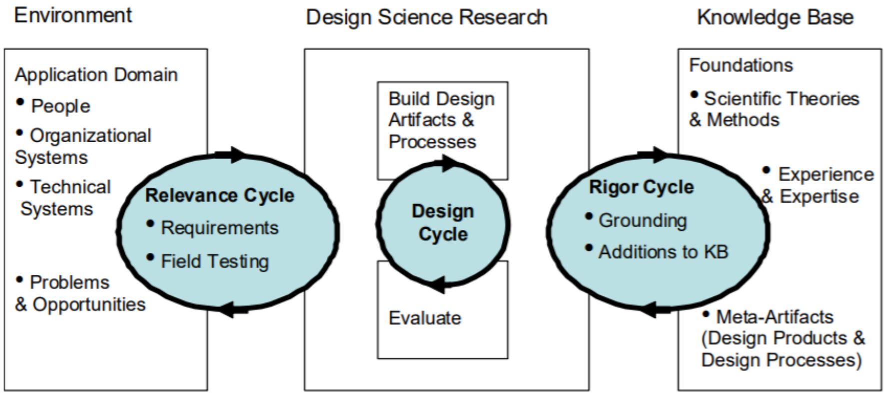

Figure 4: The three cycles of Hevner [Hevner, 2007].

- Real-time data for CBM: Data is needed to assess the current situation of an asset in real-time
- Real-world application: Data from a real situation is needed, to test if the condition monitoring system could provide use full information that can help with performing smart maintenance.

4.3.3 Decision Making Grid

A Decision Making Grid (DMG) is a grid that helps with ranking items based on the most important factors [Aslam-Zainudeen and Labib, 2011]. The DMG will be implemented to prioritize different parts of a bridge that require maintenance and suggest a maintenance strategy based on the ranking.

Chapter 5: Choosing a maintenance strategy

To determine which strategy should be used for which part a DMG can be used. The DMG concept was introduced by [Labib, 2004] and helps to identify which maintenance activities should be implemented on each system and which system should be prioritized. In the paper, Labib uses a Pareto analysis to identify the systems that caused the most problems for a train operating company. The company already made use of a computer maintenance management system (CMMS) as a database for the technical history of the assets of the company. By using the information from the CMMS and implementing it into the DMG a maintenance strategy can be obtained by detecting the worst-performing parts of a specific system [Aslam-Zainudeen and Labib, 2011]. To implement it the following three steps needs to be carried out:

Step 1: criteria analysis

With the help of a Pareto analysis of two important criteria: downtime (average) and the frequency of malfunctions, the worst-performing parts of the system can be found.

Step 2: decision mapping

By selecting scales for high, medium and low groups for both the downtime and the frequency of malfunctions a grid can be created which will suggest the appropriate maintenance strategy of a part of the asset based on the location in the grid. The grid consists of 9 squares that have an action that needs to be taken when a part of an asset is placed within it. This grid is shown in figure 5.

Step 3: decision support

The last step is to place the assets in the grid and to recommend a maintenance strategy. In the bottom left corner CM is located which can be implemented when the failures are easy to rectify and do not occur often. The action on the top left is SLU (skill level upgrade), which should be used when a problem occurs often but requires an easy maintenance task to be performed. On the bottom right, the action is CBM. CBM should be implemented in situations when a part does not break down frequently but when it does it is a big problem and has a resulting high downtime. In the top right, the worst-performing parts are located. This part needs to be structurally modified with the help of design out maintenance (DOM), a redesign of the part is necessary as no parts should be located in this area. If the part is located between low and high frequency and low and high downtime time, PvM should be implemented.

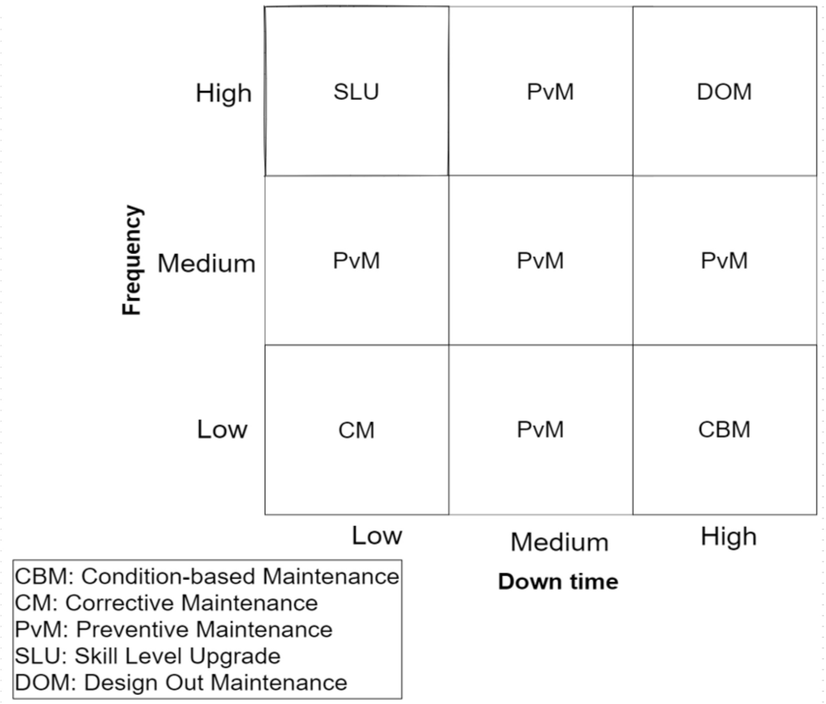

Figure 5: Decision Making Grid [Labib, 1998].

In appendix A the Pareto plots of the downtime and frequency for a specific part of the bridge is shown. This data for the downtime and frequency per part is also visible in table 2. The scales for high, medium and low are created by setting the thresholds with the formulas below which are based on the formulas from the paper written by [Seecharan et al., 2018], and are used to create the thresholds that determine in which scale a part belongs.

Medium/High boundary $= h - \frac{1}{3}(h - l)$

Low/Medium boundary $= h - \frac{2}{3}(h - l)$

Where h is the highest value in the list and l is the lowest value in the list [Seecharan et al., 2018]. The values for the thresholds are shown in table 1.

	Frequency	Downtime/Frequency
Medium/High boundary	38,66	2,713
Low/Medium boundary	21,33	2,076

Table 1: The boundary values that are used to create the high, medium, and low scales.

Now the parts (displayed by their symbol) can be placed into the DMG, the result is shown in figure 6. Based on the location of the part in the DMG a maintenance strategy is recommended. CBM is suggested for the maintenance of mechanical parts because the downtime due to a mechanical failure is high, and why the high cost of implementing CBM are justified. For maintenance relating to the overall control of the bridge, a SLU is suggested because this can ensure that the malfunctions are actually resolved quickly and lead to a lower downtime without having to make large investments. Four other parts: Electric, Land traffic signals, Camera and Steering, are located in the PvM part of the DMG in order to avoid malfunction in a cost-effective way pay performing maintenance in advance. For the other parts, the current strategy CM is still a good option because they do not occur often and do not cause much downtime. Due to the low risk of these malfunctions they can be identified and rectified on location.

Part	Symbol	Down time	Frequency	Severity	$\frac{Downtime}{Frequency}$	Severity
Barriers	A	22,116667	14	low	1,58	low
General	B	16,15	9	low	1,79	low
Audio/Video	C	5,9333333	4	low	1,48	low
Control	D	80,683333	56	high	1,44	low
Steering	E	61,4	29	medium	2,12	medium
Camera	F	40,916667	17	low	2,41	medium
Electric	G	10,583333	5	low	2,12	medium
Hydrolic	H	1,9166667	1	low	1,92	low
Land trafic signals	I	16	6	low	2,67	medium
Mechanical	J	40,25	12	low	3,35	high
Other	K	21,683333	12	low	1,81	low
Scanner	L	3	1	low	3,00	high
Shipping signals	M	9,3333333	5	low	1,87	low

Table 2

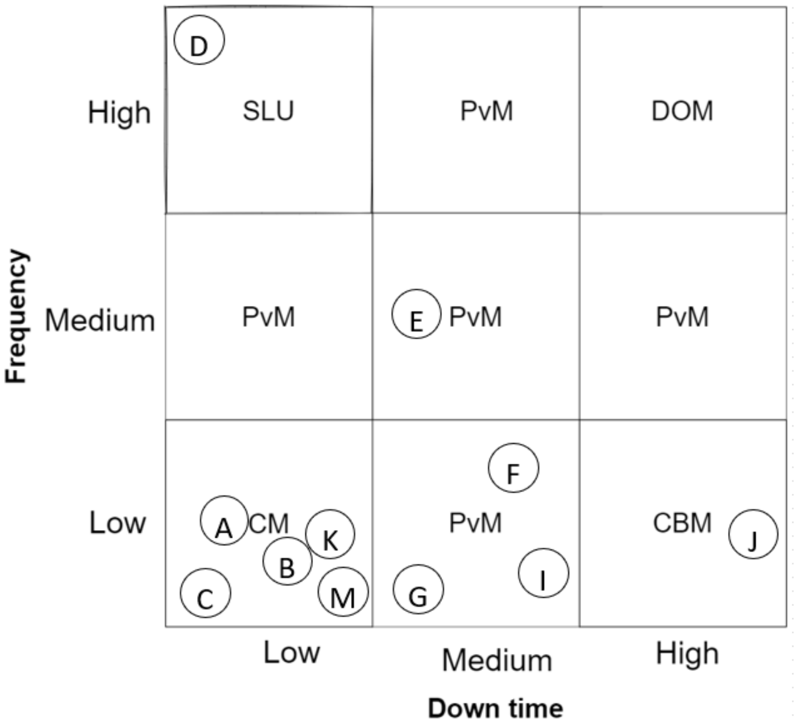

Figure 6: The different parts are placed within the DMG based on the values from table 2.

Chapter 6: Condition-based Maintenance

CBM or PdM can be best described as maintenance practices when needs arise [Morales, 2002]. This is done by monitoring the condition of the machine (or equipment) continuously or periodically depending upon the need for the availability of the machine.

6.1 Condition monitoring techniques

Currently, the most used techniques used for CBM include human senses. The condition of the equipment is being monitored by using the normal human senses such as visual observations, listening, smell and touching [Mahmood, 2011]. However, there are also other diagnostic and monitoring techniques that can be implemented to monitor the condition of an asset [Mobley, 2002]. These other diagnostic and monitoring techniques include:

- Vibration monitoring
- Acoustic analysis
- Motor current analysis technique
- Motor operated value testing
- Thermography
- Tribology
- Process parameter monitoring
- Visual inspection

For the pilot bridge in Giethoorn Noord, it was decided to use vibration monitoring as the preferred condition monitoring technique. Vibration monitoring is the most widely used and reliably technique used in the industry today [Mobley, 2002]. It does however have some downsides since it is limited to mechanical condition monitoring. To fully monitor the condition and reliability of a machine a more comprehensive pilot should be conducted that also included non-mechanical condition monitoring techniques from the above list.

6.2 Vibration analysis

Vibration analysis is the most used monitoring equipment around the world. It is estimated that currently 80% of the parameters measured for condition monitoring are obtained by vibration analysis [Pophaley and Vyas, 2010]. The reason why vibration analysis is the most widespread technique is because the vibration response gives specific information with regards to fault conditions in different kinds of machines or tools [Khwaja et al., 2010]. This vibration response is generated by every mechanical equipment in motion. Each motion generated a specific vibration profile or signature that indicated the operating condition of the machine generating the motion. This is the case regardless of the speed or whether the mode of operation is rotation, reciprocation or linear motion [Mobley, 2002]. This is another reason why vibration analysis is so widely used because it is widely applicable.

6.2.1 Theory of vibrations

Every vibration is a periodic motion that repeats after a certain interval of time. The time interval is equal to the period of the vibration and is indicated by T. The inverse of the period is called the frequency (f), 1/T, which is expressed in Hertz. A harmonic motion is the simplest type of periodic motion and describes the relation between the vibration displacement in a spectrum with amplitude, frequency and time which is expressed by the following equation [Mobley, 1999].

$$X = X_0 sin(wt)$$

Where:

X = Vibration displacement (millimeters)
X_0 = Maximum displacement or amplitude (millimeters)
w = Circular frequency (radians per seconds)
t = Time (seconds)

6.2.2 Vibration profiles

Actual vibration profiles from a machine are much more complex than the simple harmonic motion that is depicted in figure 7. When a machine is operational there are many different sources of vibrations. Each source creates a specific vibration that can be lead back to that specific source. What makes a vibration profile for a machine so much more complex is the

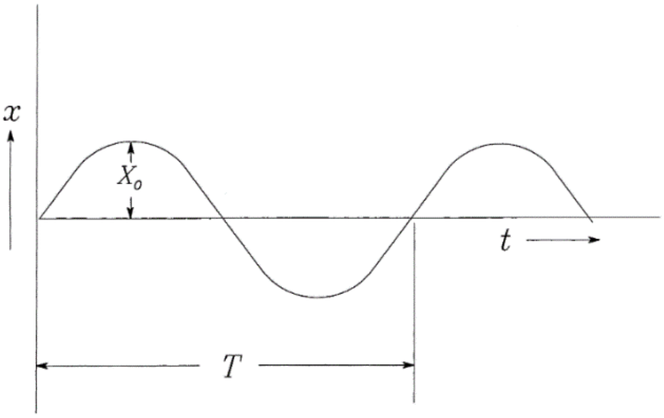

Figure 7: Example of a simple harmonic motion [Mobley, 1999].

fact that all the specific frequencies from every source are added up to each other. In figure 8 below this composite profile which consist of in this case, two different vibrations is shown. An oscillation that cannot be represented by a single harmonic function is called a non-harmonic motion [More, 2020]. The continuous line in figure 8 represents such a non-harmonic motion as it is cannot be represented by a single harmonic motion like the dashed lines in the figure. In real-world applications this complex profile consists of much more distinct frequencies and also noise is present in the signal. To analyze this complex vibration profile the difference between the time domain and frequency domain should be clear.

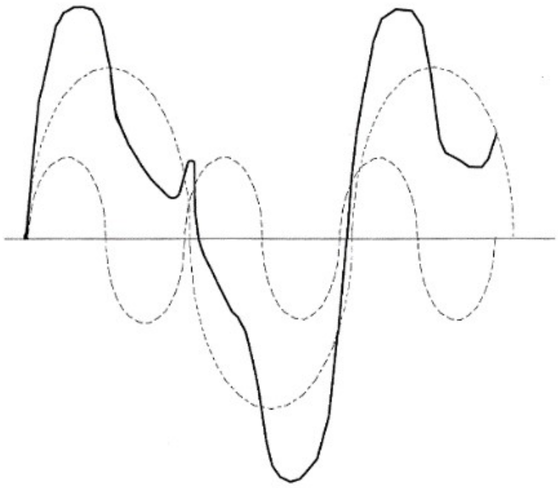

Figure 8: The continuous line is a non-harmonic motion while the dashed lines are harmonic motions [Mobley, 1999].

6.2.3 Time Domain

Vibration data can be displayed in the time domain by plotting the amplitude against the time. Where the amplitude is the maximum value of a motion or vibration represented in terms of displacement, velocity or acceleration [Mobley, 1999]. Plotting the vibration data in the time domain is useful for monitoring by analyzing the overall changes of a machine over time. However, for rotating motion machinery, such as an electric motor or gearbox it is difficult to use the data in the time domain for a more specific analysis. This is because all the vibrations are added up to each other in the time domain. The power of all the different sources is added up to each other to a total amplitude, which makes it hard to see the contributions of one specific source to the overall amplitude. To analyze the operating condition of a machine in more detail the frequency domain should be used.

Frequency Domain

French physicist and mathematician Jean Fourier discovered that every non-harmonic motion is the sum of multiple simple harmonic functions like the one in figure 8. He stated that any periodic function can be represented by a series of sine functions with different frequencies. The equation that describes this phenomenon is called the Fourier series and looks as follows [Mobley, 1999].

$$F(t) = A_0 + A_1 sin(wt + \sigma_1) + A_2 sin(2wt + \sigma_2) + A_3 sin(3wt + \sigma_3) + ...$$

Here the terms $2w$, $3w$, etc. are the harmonics of the primary frequency w. In most rotating machines the primary frequency is equal to the running speed of the rotor shaft [Mobley, 1999]. Besides the primary frequency or first harmonic, a second, third or other multiples of the running frequency can also be included in the signature of a complex vibration. However, these frequencies which originate from the rotation component are always a multiple of the running speed of the motor shaft [Mobley, 2002]. Determining these frequencies is an important step in analyzing the operating condition of the machine.

To find these specific frequencies from the complex vibration the signal has to be converted from the time domain to the frequency domain using the (Fast) Fourier Transform (FFT). Once the vibration is converted to the frequency domain each vibrancy component of the complex vibration from the machine can be found by looking for their respective peak in the frequency domain plot. In this plot, the amplitude of a specific frequency is located on the

Y-axis while the frequency is located on the X-axis. Such a frequency domain plot is also called the vibration signature. An example of a frequency plot is shown in figure 9.

For transient signals, such as faulty bearings or discrete tooth errors that occur at a high frequency a special High frequency-FFT (H-FFT) analysis can be used. In the H-FFT analysis, the machine noise and vibration other than high-frequency transient vibrations are removed by implementing some upstream filters and mathematical operations to separate the signals [ifm,].

The most important part of vibration analysis in the frequency domain to detect and predict failures is the ability to make a distinction between normal and abnormal vibration profiles. In a machine, there are a lot of normal frequencies such as the frequencies that originated from the rotation of the rotor shaft or the bearing in an electrical motor, or the gear inside a gearbox. The focus should lay on the frequencies that are not expected and could indicate a problem. For example, a loose bolt, worn bearings or a misaligned shaft would generate an unexpected frequency which can be detected in the frequency domain plot. Because in the pilot project the sensors are being installed on the gearmotor, which consist of gearbox and a motor some failure frequencies for both parts are discussed in the next subsections.

6.2.4 Electric motor

To evaluate the operating condition and detect any failure warnings the following parameters of the electric motor should be monitored:

- Running speed: As was said before the running speed of the motor determines the harmonics of the running speed of the motor which is important for further analysis.
- Line frequency: The line frequency is equal to the alternating current being supplied to the machine. In Europe, this is equal to 50 Hz. The first three harmonics of this fundamental frequency should be monitored for detecting any electric problems which are associated with the incoming power to the machine. So these are the first harmonic (50 Hz), second harmonic (100 Hz) and third harmonic (150 Hz).
- Imbalance: occurs on all rotating shafts and results from a mass around the shaft that is unevenly distributed. Imbalance increases the wear on the bearings of the shaft and is therefore undesirable. To detect imbalance the harmonics of the running speed play an

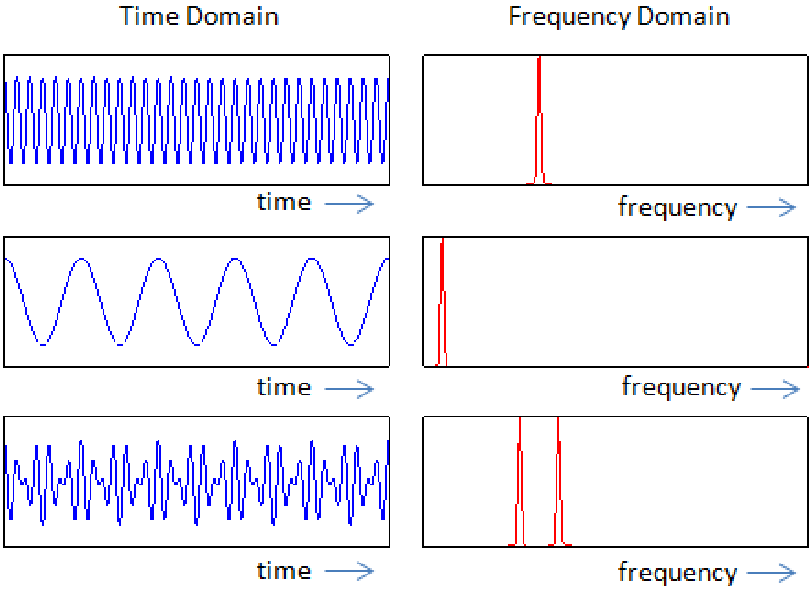

Figure 9: The two top left plots are of harmonic motions in the time domain, while they are depicted in the frequency domain on the right side. The bottom left plot is of a non-harmonic motion in the time domain, in the frequency domain this signal has two distinct peaks.

important part. The presence of the third harmonic of the running speed is an indication of imbalance within an electric motor [Mobley, 1999]. The third harmonic is found in the frequency domain plot whenever there is axial thrusting of a rotation element, which can be a result of the imbalance of the motor. Another indication for imbalance is the line frequency. Modulations or harmonics of line frequencies can be an indication of the motors inability to hold magnetic centre which can be a result of unbalance.

- Slip frequency: is the difference between the actual running speed and the synchronous speed. The synchronous speed can be calculated with the following formula [Lee et al., 2018].

  $n_s = 120 * \frac{f}{p}$

  f = line voltage in Hz
  p = number of poles
  n_s = synchronous speed in rpm

The gearmotor of the pilot bridge has a motor with a three-phase, 4 pole electric motor. The motor thus has a synchronous speed of $120 * \frac{50}{4} = 1500$ rpm.

- Loose Rotor Bars: Loose rotor bars can be detected by looking at the sidebands around the line frequency. These sidebands are a function of the number of poles in the motor and the slip frequency [Pro, 2004].
- Bearing frequencies: Electric motors incorporate either sleeve or rolling-element bearings. A narrow-band window should be established to monitor both the normal rotational and defect frequencies with the type of bearing used for each application.

6.2.5 Gearboxes

The gearbox is used to change the speed of the motor to the desired speed. The drive shaft of the motor has a rotational speed of 1468 rpm, the gearbox changes this to an output rotation speed of 33 rpm. This gives the gearbox a gear unit ratio of $1468/33 = 44.49$.

- Running speed: Each of the running speeds in the gearbox should be monitored. The number of running speeds depends on the number of gear sets in the gearbox.
- Bearings: Similar to the bearings in the electric motor a narrow-band window should be established to monitor the defect frequencies of the specific bearings that are used within the gearbox.
- Gear-Mesh Frequencies: Each gear set generates a unique profile of frequency components that should be monitored. The gear-mesh frequency can be calculated by multiplying the number of teeth of the pinion (small) or drive (large) gear by the rotational shaft speed [Mobley, 1999]. The fundamental gear-mesh frequencies should be monitored by looking for sidebands that surround the fundamental gear-mesh frequency. The presence of sidebands and harmonics of the gear-mesh frequencies can indicate potential alignment or wear problems in the gear set.

Chapter 7: Case study

Before the equipment for monitoring systems are purchased it is important to look at other research that is done in this field to see if CBM maintenance is possible and beneficial in the case of bridges. One example is a monitoring system that was implemented on the Sunrise Bridge (Florida) to perform CBM on critical mechanical, electrical and structural components [Catbas et al., 2013]. The two main critical mechanical components of the bridge in Giethoorn Noord are the gearbox and the electrical motor. In the project that was implemented on the Sunrise Bridge, these mechanical parts were also being monitored.

Gearbox

Accelerometers were installed on the gearbox to detect potential deterioration or lack of lubrication by looking at the changing characteristics of the vibrations generated by the gearbox. The largest and smallest 30 values for the opening and closing sequence were collected each day and the standard deviation and root mean squares of the accelerometers were calculated for each opening and closing action. With this data, which can be found in the same report by [Catbas et al., 2013], the team detected an anomaly in the gearbox due to a sudden increase in the vibration levels.

Electrical motor

To monitor the electrical motor three different sensors were used: An ammeter to measures the phases of the electric motor, infrared temperature sensors to measure the temperature of the electric motor and again accelerometers to measure the vibrations generated by the motor during opening and closing events [Catbas et al., 2013].

The data from the opening and closing sequence of the bridge are displayed in figure 11. The data is collected from the accelerometers that were placed on both the gearbox and the motor.

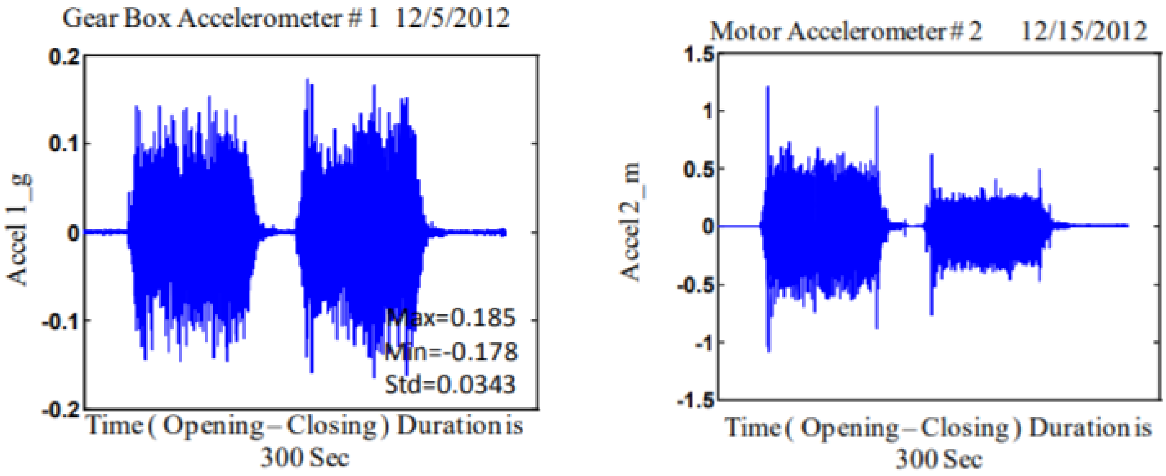

Figure 10: The data of the two images are collected from the Sunrise Bridge and come from the paper written by [Catbas et al., 2013]. On the images, the acceleration is located on the y-axis and the time is located on the x-axis. The acceleration is depicted in g, where one g is equal to 9.8 m/s^2.

Chapter 8: Pilot project

For this pilot project maintenance using CBM is explored to see what advantages and disadvantages such a maintenance strategy has compared to the current CM strategy. CBM based on vibration analysis is performed on the gearmotor at the bridge in Giethoorn Noord. This bridge was chosen because there are plans to build a new bridge on this location. By analysing the current drive system the province can decide whether or not a new motor or gearbox is necessary or whether the current system can be transferred over whenever the new bridge will be built. In this chapter the system requirements, hardware selection/installation and results of the pilot thus far are discussed.

8.1 System requirements

- Remote access: The system should be able to be monitored remotely with the help of remote access. It should enable remote users to access the measurement data from the bridge in real-time. Data security is of course important when using a remote access solution. Therefore it is required to have a secure and private connection to prevent any unwanted access to the data.

- A separate system with respect to the current control of the bridge: The system should not interact with the current control of the bridge in any way. This is why the sensors will not be connected to the PLC (Programmable logic controller) of the bridge. The PLC is an industrial computer that is used for many functions for example the remote control for opening and closing the bridge.

- High-frequency range and sampling rate: A high-frequency range is needed to detect faults with relatively high frequencies such as gear and bearing faults. To capture these higher frequencies a high sampling rate is necessary. Nyquist theorem states that periodic signals must be sampled at more than twice the highest frequency component [Oshana, 2006]. So if a maximum frequency of 10 kHz should be captured a sampling rate over 20 kHz is necessary.

- Raw data (FFT and H-FFT analysis): To perform a signature analysis the raw data is needed to create a frequency domain plot. Some systems have this capability to access the raw data but other solutions apply a pre-filtering where data is collected over a specified time and the highest values are collected for further installation. Although this is useful for overall trend analysis, for making actual estimates on where a problem might be located based on a frequency spectrum the raw data is needed.

- Narrowband functionality: With a narrowband analysis the data can indicate the specific frequency component that is responsible for the vibration signature [Mobley, 1999]. This is possible by a user-selected band of frequency components, which helps with monitoring the fault-frequencies that are of interest and not include the vibration from other components. When only broadband is available the data does not give this indication of which specific component is responsible for the vibration signature. This makes finding the actual frequencies of a potentially faulty component a lot more time-consuming.
- The current system should not be tampered with: The goal is to make a monitoring system that can be placed and removed easily from the machine it is monitoring. Because this is a pilot project the vibration monitoring equipment will be placed on the gearmotor of the bridge for a limited time. After the removal of the equipment, the bridge should look and work as it did before the pilot. It is therefore required that the vibration sensors are placed on the gearmotor with either a magnet or an adhesive, and not with a screw connection which is the recommended method for permanent installations.
- Industrial solution: The monitoring system should be made up of industrial products that are specifically made for use in industrial environments. This means that the equipment should work reliably for long periods and conform to all the standards set for their respective product class.
- Easy access to the data: The data from the sensor should be easily accessible. Therefore the preference at least during the pilot project is to store the data locally as opposed to using a cloud surface to store the data. This saves time of setting up a cloud storage system and gives the company more control over how to access the data during this pilot.
- Possibility of data logging: By logging the data it can be analysed in more detail to detect any failures. It allows the comparison of the different frequencies plots over time

to see if there are any new peaks that need further analysis to see what is the cause of this specific frequency in the plot.

- Trend analysis: Long term trending of the overall machine conditions can help to use predictive maintenance to detect faults at an early stage. By logging different parameters such as the a-RMS en the a-peak value over a long time the overall condition of the machine can be monitored. When an ascending trend is visible it can be an indication of a failing part, a frequency analysis can be performed to determine what could be the problem for this increase.

8.2 Hardware selection

For the pilot, meetings have been held with companies that already have a lot of experience in CBM and PdM and have the necessary equipment to execute the pilot. After the meetings, the following hardware was chosen because it best matched the requirements that were set.

- ServiceGate V2/LTE (industrial router): This gateway helps to easily access any devices that are connected to one of its LAN ports. However, the main advantage of this particular gateway is that it has a module that uses a SIM card to connect to the internet by 4G/LTE. Since there is no internet connection available at the location in Giethoorn Noord, this feature will make it easy to set up a reliable internet connection. The gateway uses a VPN which enables it to connect individual users to private networks. The associated Client software is needed to create the connection to the ServiceGate V2. The VPN also encrypts the data for a safe transfer. The ServiceGate v2 will allow for easy remote access and it is easy to access the data.

- VSA005 (accelerometer): This is a capacitive sensor for vibration detection of machines and equipment. This sensor has a frequency range of 1 to 10000 Hz which enables it to detect faults at a higher frequency such as bearing faults that happen at a frequency a couple of times the rotating speed of the gearmotor. Furthermore, it has a measuring range of 50 g which is more than enough for the vibration analysis since no vibrations larger than 2 g or lower than -2 g were detected when a first test sensor (Bosch XDK) was placed at the bridge in Giethoorn Noord. Because the VSA005 is a capacitive sensor it has the advantage of performing a self-test as opposed to piezoelectric sensors which is the other measuring principle used for accelerometers. With this self-test, the proper functioning of the sensor can be tested remotely. Another reason why this sensor was chosen is that it allows for the collection of raw data. Other sensors that were considered worked via IO-link which is a point to point communication that links sensors to the PLC or industrial ethernet. The disadvantage of IO-link is that it cannot transfer the large amount of data that is necessary for raw data collection. This would mean that a spectral analysis would not be possible. The VSA005 sensor can transfer a large amount of data, which is one of the reasons it was chosen over IO-link sensors.

- E30491 (magnet mount): One of the system requirements was that the current system should not be tampered with. For this reason, a magnet mount is selected to attach the vibration sensors to the gearmotor. They offer a convenient way to temporary attach the sensors to magnetic surfaces. The downside of using a magnetic mounting is that the frequency range is limited to in this case 3 kHz. For a permanent installation of sensors, a screw connection would be recommended as this allows a frequency range up to 15 kHz. For this project, the frequency range the 3 kHz is enough to measure overall machine vibration that could indicate an upcoming failure, the ultra-high frequencies needed to measure the cavitation in a pump, but that is irrelevant for this pilot.
- VSE003 (diagnostic electronics): The diagnostic module allows for online monitoring of process values and dynamic signal (vibrations) in the time domain or frequency domain (FFT and H-FFT). Furthermore, the module has an internal trend memory with an RTC (Real-time clock) timestamp that can store up to 881664 data records and use FIFO (First-In, First-Out) memory structure. The module works in conjunction with the parameter software VES004. With this software, the data from the diagnostic electronics can be configured and displayed.
- DN1031 (power supply): The device is used for the regulated 24VDC voltage supply for the diagnostic electronics and the industrial router. The power supply has an efficiency of 88 % and has built-in safety features such as overload protection and it is short-circuit proof.

8.3 Hardware installation

Mounting of the sensors on the gearmotor:

The gearmotor that will be monitored consist of an electric motor and a gearbox. Therefore two acceleration sensors will be used to measure both parts.

Sensor 1 (Motor):

The measuring direction should be in the direction of the main vibration. In the motor, the main vibration is in the radial direction of the shaft. The mounting point should be located close to the support of the shaft. The sensor is placed on the motor driven end (MDR) of the electric motor.

Sensor 2 (Gearbox):

For the gearbox, the main vibrations will be in the vertical direction of the gearbox. The accelerometer is therefore placed on the side of the gearbox on a flat surface for the best result.

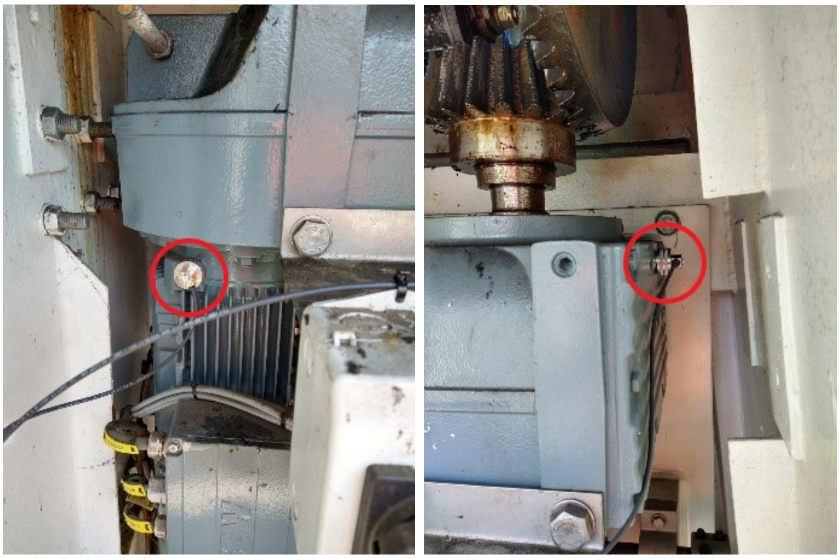

Figure 11: On the left sensor 1 which is installed on the MDR is shown, while on the right sensor 2 which is located on the side of the gearbox can be seen.

The rest of the equipment is placed inside a DIN rail enclosure box. Inside this box, all the equipment is mounted on standard DIN rails. Because industrial equipment was purchased all the equipment is mountable by DIN rails.

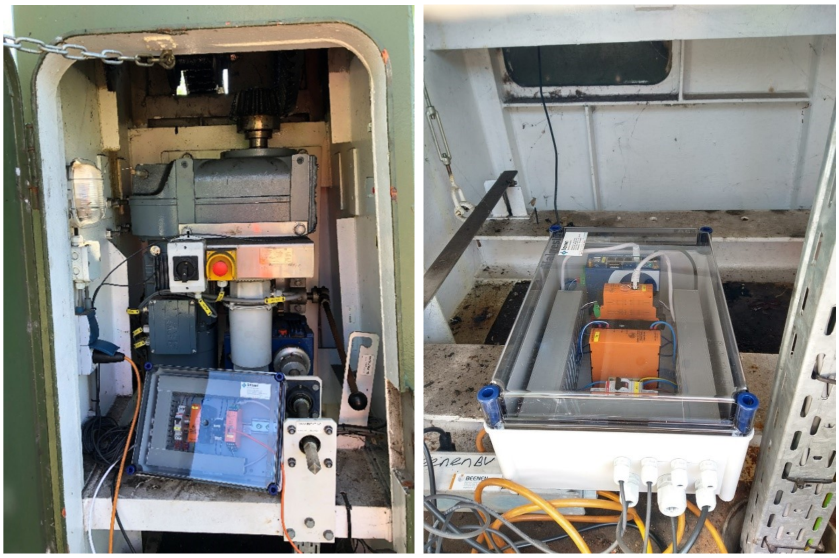

Figure 12: In the right image from top to bottom the industrial router, diagnostic equipment and the power supply is shown. On the left image, the power supply and diagnostic equipment are shown inside the DIN rail enclosure box (the industrial router was not yet installed).

Antenna installation:

To ensure a good remote connection to the industrial router a 4g antenna is installed outside the metallic enclose that hold the gearmotor (figure 13). A signal strength of -81 dBm is obtained with this antenna, which means that good signal strength is present as can be seen in table 3 below.

Figure 13: The antenna is installed outside the metallic enclosure.

Signal Strength (dBm)	**Connection**
>-60 dBm	Excellent
-60 to -89 dBm	Good
-90 to -99 dBm	Fair
<= -100 dBm	Weak

Table 3: Connection quality based on the signal strength in dBm [Kontogianni and Alepis, 2017].

8.4 Results

In appendix B the three main parameters that can be collected from the VSE003 module are shown. The data was collected during an opening and closing sequence for each parameter. The parameters are v-RMS (velocity-RMS), a-RMS (acceleration-RMS), and a-peak (acceleration-peak). The RMS (Root Mean Square) values show the energy content of the vibration and therefore also the destructive power of the vibration [Lebold et al., 2000]. The peak value is the highest value that occurred during a set interval. v-RMS monitors the velocity and gives an indication of the overall fatigue of the machine structure. a-RMS monitors the acceleration and gives an indication of any friction present. The a-peak value can indicate any resonances and bearing defects in the gearmotor. The warning and damage limits that can be seen in each figure are based on the ISO 10816 standard in the case of the v-RMS values, while the warning and damage limits for the a-RMS and a-peak values are chosen by the supplier based on the gearmotor specifications. However, these limits should be determined based on the data from a longer period. In the figures, we can see that all values are below the current warning limit. The maximum values are 1.5 m/s, 1 m/s^2, and 15 m/s^2 for respectively v-RMS, a-RMS, and a-peak.

The first indication of an upcoming failure can be often spotted by performing a trend analysis. However, due to the limited time of the project, the data could only be collected from the period between 28-05-2021 and 22-06-2021. The trend history can be downloaded remotely from the diagnostic electronics. The diagnostic module safes the highest value that occurred during an interval of one minute of the three main parameters automatically. In appendix C the history of the v-RMS, a-RMS and a-peak values for sensors 1 and 2 can be seen. No clear upward trend is visible here, which indicates that the gearmotor is running correctly. However, when the values are compared to the data in appendix B, outliers can be spotted. This is clearly visible when looking at the a-peak values from sensor 1, here you see that most points are around 15 which was expected but there are also outliers visible. These could be caused by the heavy traffic that drives over the bridge, but this requires additional research.

To see if any specific problem can be detected the data is analyzed in the frequency spectrum. In the H-FFT analysis which is used to discover transient signals, which can indicate faulty bearing or discrete tooth errors, peak frequencies with harmonic behaviour can be seen. In the

H-FFT spectrum of sensor 1 which is located on the MDE, peak frequencies can be observed (figure 14). In this figure, the harmonics are indicated by the purple lines.

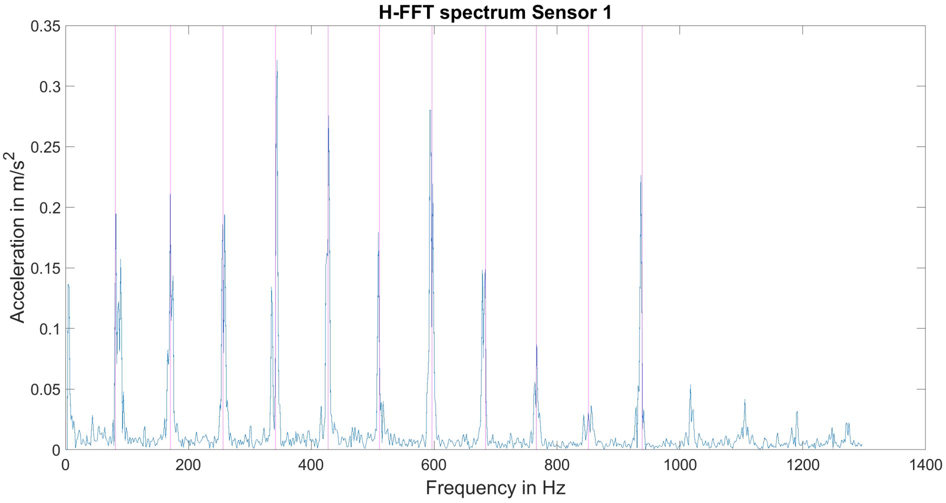

Figure 14: H-FFT spectrum of sensor 1, the peaks are the result of a transient signal which can indicate a faulty bearing or a discrete tooth error. The purple lines indicate the harmonic behaviour of the signal. On the y-axis, the acceleration in m/s^2 *is shown, while on the x-axis the frequency is shown in Hz.*

Looking at the FFT spectrum another peak can be seen at higher frequencies. Here there are also sidebands visible which are indicated in red in figure 14 below. These sidebands often occur around the defect frequencies of bearings.

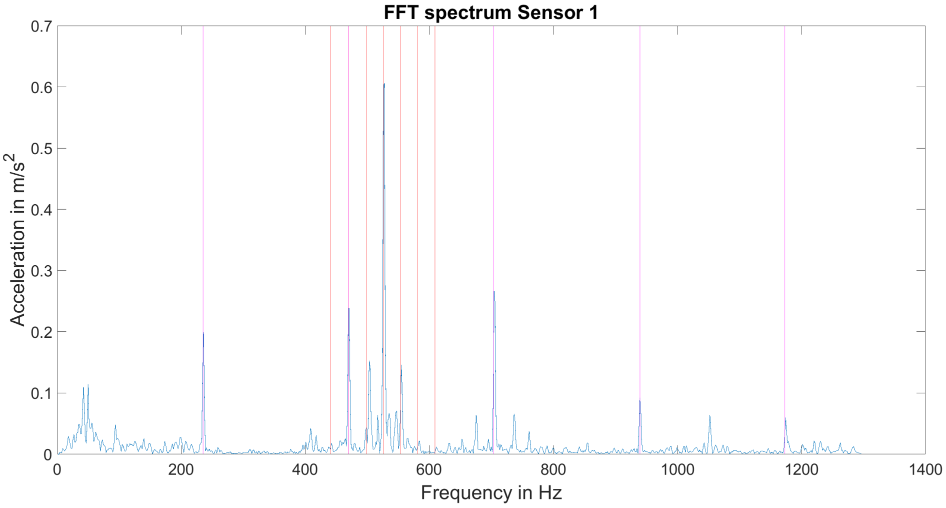

Figure 15: FFT spectrum of sensor 1, sidebands are indicated by the red lines.

A bearing consist of four components that are prone to failure due to wear:

- Ball passing frequency outer race (BPFO): Local fault on the outer race.
- Ball passing frequency inner race (BPFI): Local fault on the inner race.
- Fundamental train frequency (FTF): Fault on the cage or mechanical looseness.
- Ball fault frequency (BFF): Local fault on the rolling elements.

The values for BPFO, BPFI and BFF can be found in a bearing database within the VES004 software. The value for FTF can be approximated by: FTF = 0.4 X RPM/60 [Fernandez, 2020]. The electrical motor has two ball bearings, 6309-C3 and 6209-C3. The frequency factor which indicates the location of the fault frequency of the four components can be found in table 4.

Looking back at figure 14 the first peak is located at a frequency factor of around 3.3 (80.75 Hz). The frequency factor is based on the rotational speed of 1468 RPM. A frequency factor of 1 is equal to 24.47 Hz, so a frequency factor of 3.3 is equal to 3.3 x 24.47 = 80.75. This is closed to the BPFO frequency of the 6309-C3 but is not exactly that 3.037 that was obtained from the bearing database. If the fault is indeed created by a local fault on the outer race the

	BPFI	BPFO	BFF	FTF
6309-C3	4.963	3.037	3.912	0.4
6209-C3	5.946	4.054	5.095	0.4

Table 4: The frequency factors of the 4 components which are prone to failures for the 6309-C3 and 6209-C3 bearing. The BPFI, BPFO, and BFF factors are taken from the database within the VES004 software while the FTF factor is from [Fernandez, 2020].

peaks can be explained as the result of the interaction between the outer race and the rolling elements. This principle is shown in figure 16, the BPFO is the frequency at which the balls pass over a single point (in this case a defect) on the outer race of the bearing.

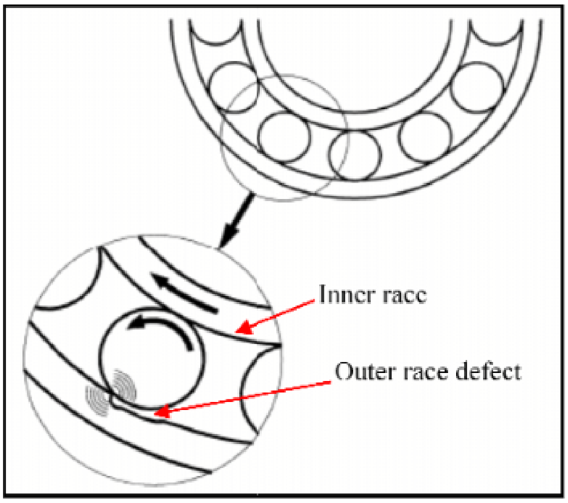

Figure 16: Defect in the outer race causes a shock impulse to spread through the bearing's components and machine structure, this results in the peaks in the HFFT spectrum [Muhammad et al., 2011].

Chapter 9: Discussion

By the performed literature research the main maintenance strategies that could be used were found. And by implementing the DMG model these different strategies could be recommended to a specific part by prioritization based on past malfunctions. Based on the completed DMG a CBM approach was recommended for the maintenance of the mechanical parts of the bridge.

The DMG was based on the malfunction that occurred during the last two years. However, Because the province did not fully keep track of the data from past failures, the failure analysis that was performed had to be based on data that was present. If everything had been properly maintained, more information would have been available about the actual blockage time as a result of a failure, now the downtime had to be used. When a malfunction occurs, this does not always mean that there is also a blockage for land and water traffic.

Vibration monitoring was selected as the preferred condition monitoring technique. Vibration sensors were installed on the gearmotor of the chosen pilot bridge in Giethoorn Noord. The high investment costs are justified because a problem with the gearmotor will not only lead to high maintenance costs but also high downtimes as was seen in the DMG. The necessary hardware was selected based on the system requirements. One of the biggest advantages of the selected hardware is that the vibration data can be analyzed both in the time and frequency domain. From the initial trend analysis which is done in the time domain, no real increasing trend is currently visible. However, the vibration monitoring equipment is at the time of writing only installed on the bridge for a couple of weeks which means that the overall condition of the gearmotor using a trend analysis over a long period was not yet possible.

The gearmotor was also analyzed in more detail in the frequency domain. Here some interesting results were obtained from the sensor located on the electrical motor. Distinct peaks show up in the H-FFT spectrum which could indicate a bearing failure. Looking at the four bearing failure frequencies it matches the BPFO, which indicates a local fault on the outer race the best. At the moment it cannot be said with certainty that is indeed a bearing problem. A discrete tooth error could also cause harmonic peaks in the spectrum. That said the harmonic peaks in the H-FFT spectrum in combination with the peak with sidebands that show up in the FFT spectrum do make a strong case for a bearing problem. Because the peak values are still low, it is not necessary to immediately take action, but it is something that has to be closely monitored. If the values become higher in the future it is advised to carry out further research and perform maintenance if necessary before the electrical motor is no longer operational.

In the case study by [Catbas et al., 2013] CBM was implemented on the Sunrise bridge in Florida using accelerometers among other sensors. The raw data from an opening and closing sequence for both an accelerometer located on the electrical motor and the gearbox are shown in figure 17. Here also the raw data from an opening and closing sequence from both sensors on the pilot bridge are shown. Even though the Sunrise bridge is many times larger, the data is very similar and the values are in the same order of magnitude. As was said in Chapter 7 the highest peak values and RMS values were collected and analyzed over a longer period, which is similar to what the set up at the pilot bridge also collects. What is different is that the case study does not use FFT analysis to look at the condition of specific components within the gearbox and the electrical motor. Instead, the research focuses more on finding correlations between the data from the different sensors that were installed on the bridge.

Further research can be conducted by implementing different CBM techniques that make use of different sensors. When different kind of data is collected the data can be correlated like in the paper by [Catbas et al., 2013] to look at potential correlations between for example the temperature, noise and vibration data. This can help to understand specific patterns and to see what is normal and abnormal. Further research can also be conducted to say with certainty what is the cause of the current peaks in the frequency domain and whether it is indeed bearing damage.

9.1 Evaluation of working within the company

The overall experience of working within the company was very positive. Of course, the time I spend working at the company was different to usual due to the corona pandemic. This meant that my normal workweek consistent of two days working on-site and the other 3 days working from home. Working from home was sometimes challenging if I wanted to quickly discuss something with colleagues, fortunately, everyone was easy to reach via online means. When I was working on site I also tried to keep people informed about the progress of the project. This

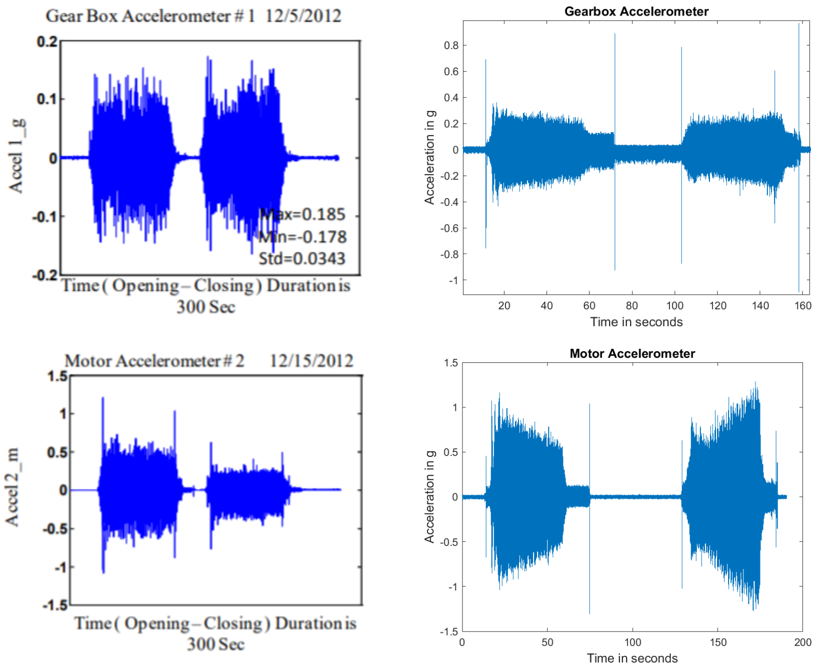

Figure 17: The data in the two images on the left are collected from the Sunrise Bridge. The images come out of the paper written by [Catbas et al., 2013]. The images on the right are collected from the bridge in Giethoorn. In all the images the acceleration is located on the y-axis and the time is located on the x-axis. The acceleration is depicted in g, where one g is equal to 9.8 m/s^2.

was also done by given a mid-term presentation to keep everyone interested and excited in the project and share intermediate results. The corona pandemic also had its advantages, one example being getting in touch with different companies for vibration monitoring equipment. From all the companies I got a quick response and a meeting was easily organized via Microsoft Teams. Because these meetings took place online, it was easier for companies to start the conversation and explain what hardware or software could be supplied for the pilot project. The technical account manager of Beenen was also present during these discussions with the various companies. How to lead these conversations is also something I learned during my time with the company. It was a new experience for me to have a conversation with a salesperson who also wants to fulfil the commercial purpose of his own company. It is therefore always important to enter the conversation well prepared so that you know what you do and do not want.

9.2 Analysis of MDP

3 pros:

- A big pro of the project was that the vibration monitoring system could actually be installed on the bridge and that a vibration analysis could be performed on the gearmotor.
- The interest from other companies to get involved with the project was very positive for both me and Beenen. Ifm, the company that supplied the hardware for the vibration monitoring, was an example of this. Even after the installation, they were still involved in the project.
- During the project, I worked with all kinds of different sensors. Most have never actually been used on a bridge, but I have learned a lot about the different possibilities and the programming of different smart sensors.

3 cons:

- The project was very wide what made it hard to be completed within 14 weeks. This meant that the project had to be scoped and that not everything could be included in the analysis. For example, the locks were excluded due to the limited time.
- CBM using vibration monitoring could only be installed on one bridge.
- Due to the limited time, it could not be said with certainty at the end of the project whether there is indeed something wrong with the bearing. If there had been more time, this would have been something that could have been sorted out.

Chapter 10: Conclusion

The goal of this design project was to design a smarter maintenance strategy for the bridges, to decrease the cost or increase the reliability. Different maintenance strategies and their advantages and disadvantages were discussed. The answer to the question of which maintenance strategy is most cost-effective/results in the highest reliability does not have one simple answer. Different strategies are suitable for different situations. By using the DMG different strategies could be recommended for different parts of the bridge by looking at data from previous malfunctions. One example of a strategy recommended to a part was the use of CBM for mechanical parts. The use of CBM was further investigated by applying vibration monitoring to a pilot bridge in Giethoorn Noord. From the data that was gathered during the last weeks of the project unexpected data that could be caused by bearing damage was observed. These values are still low at the moment but need to be monitored in the coming time to make sure they do not increase. If this is indeed caused by bearing damage, timely maintenance can be carried out to ensure that the condition of the engine does not deteriorate further and prevent the engine from breaking down.

Appendix A: Pareto plots

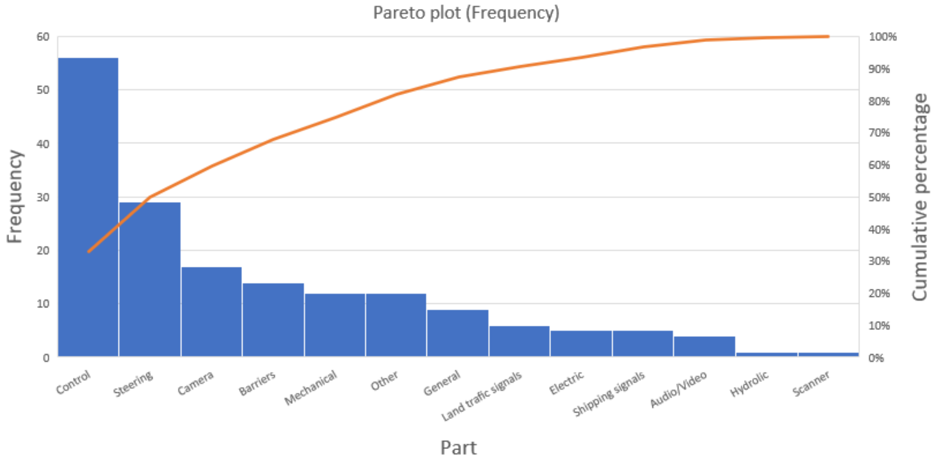

Figure 18: Pareto plot of the different parts, on the left y-axis the number of malfunctions are displayed while on the right y-axis the cumulative percentage is shown.

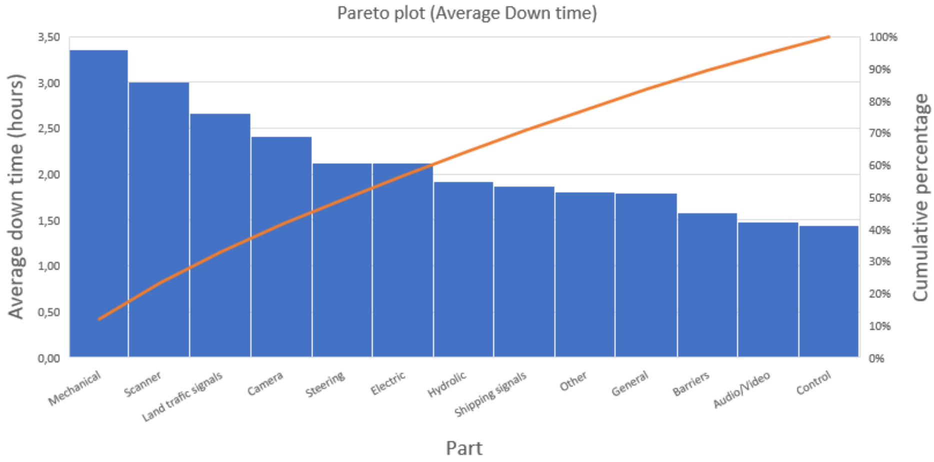

Figure 19: Pareto plot of the different parts, on the left y-axis the average downtime in hours is displayed while on the right y-axis the cumulative percentage is shown.

Appendix B: Data opening and closing sequence

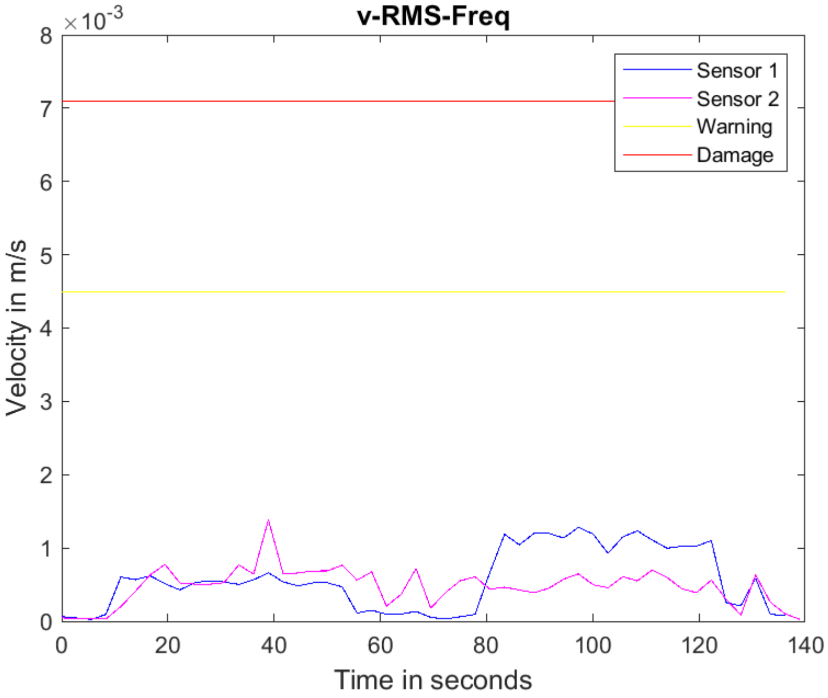

Figure 20

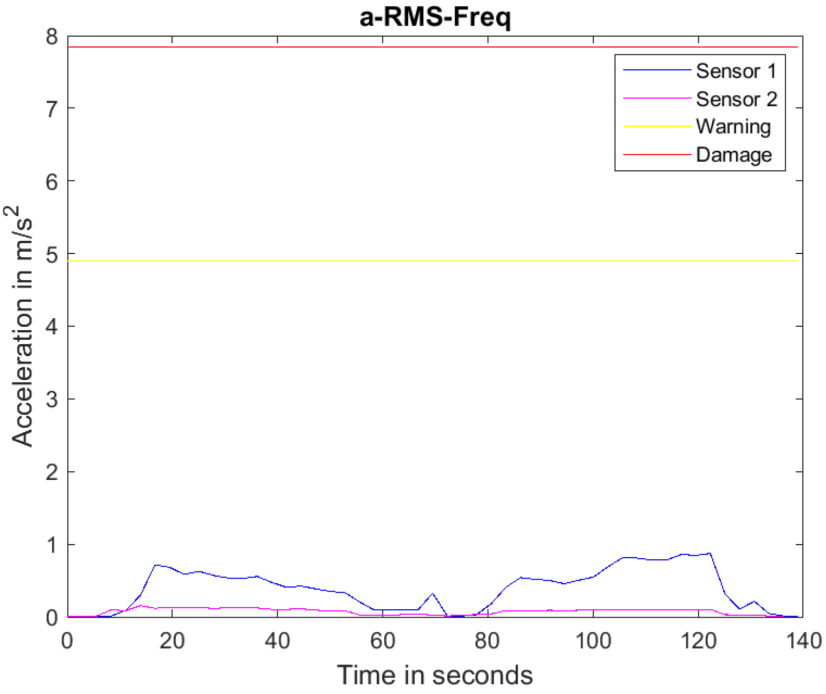

Figure 21

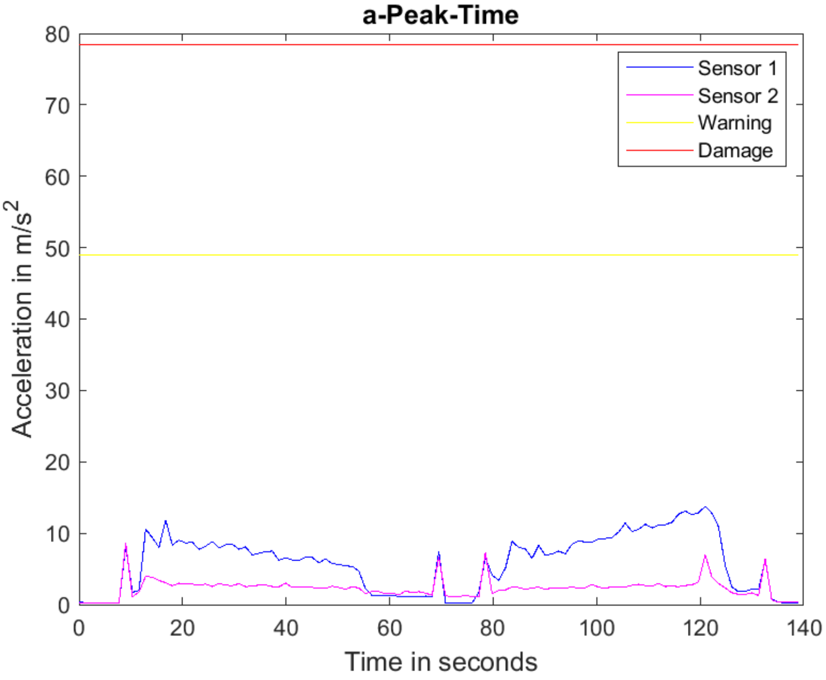

Figure 22

Appendix C: Trend analysis

C.1 Sensor 1

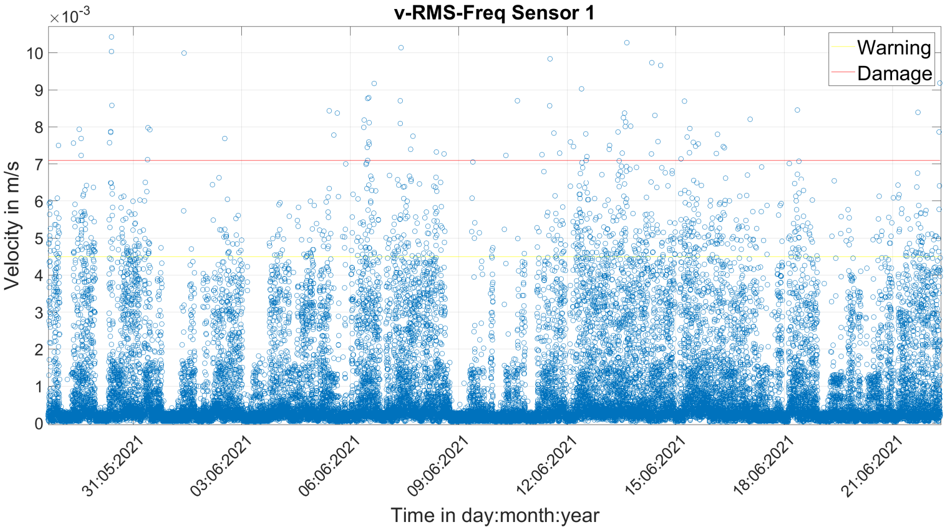

Figure 23

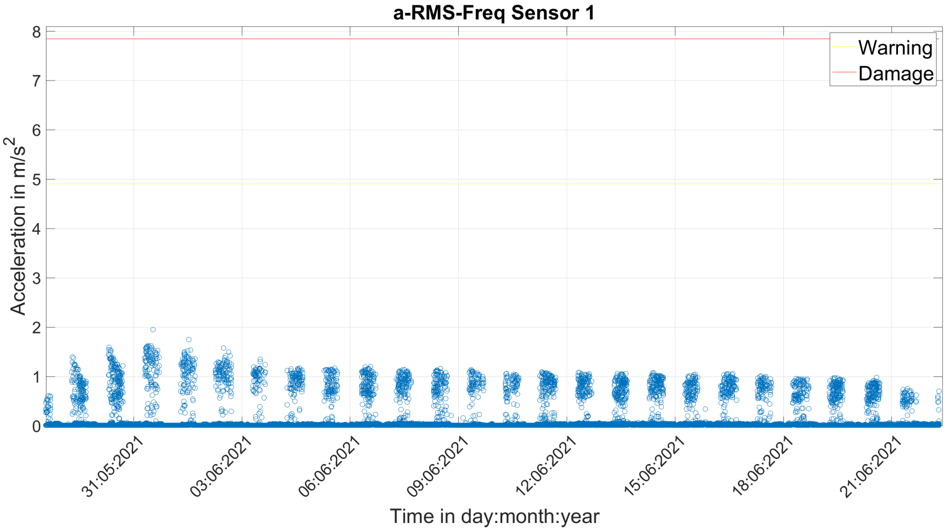

Figure 24

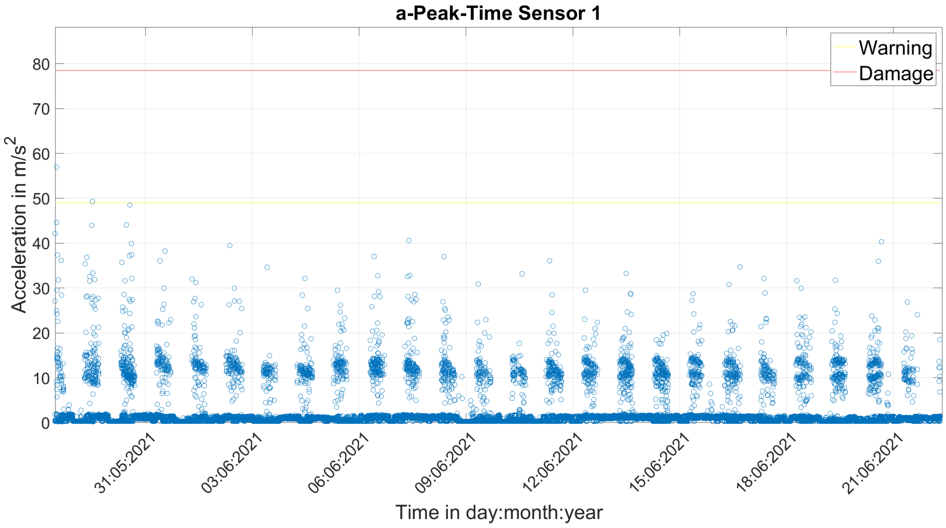

Figure 25

C.2 Sensor 2

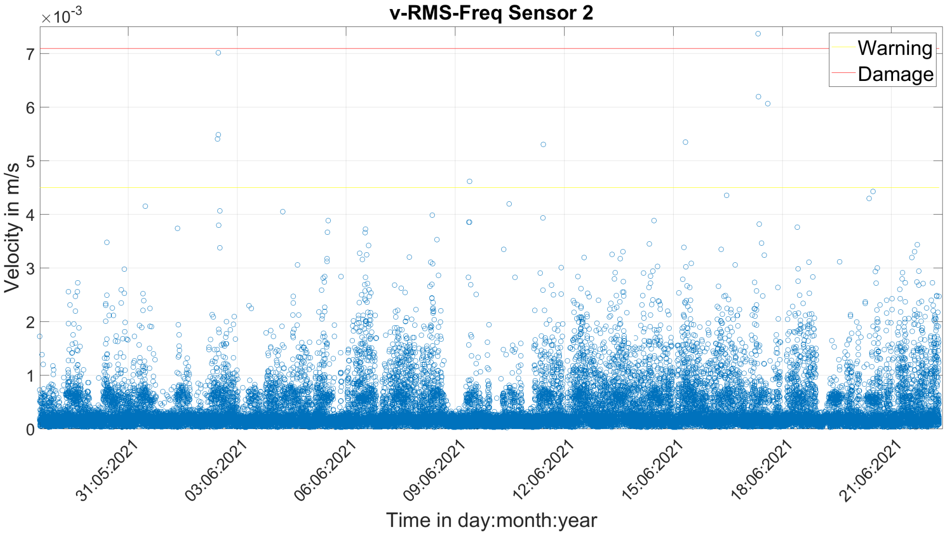

Figure 26

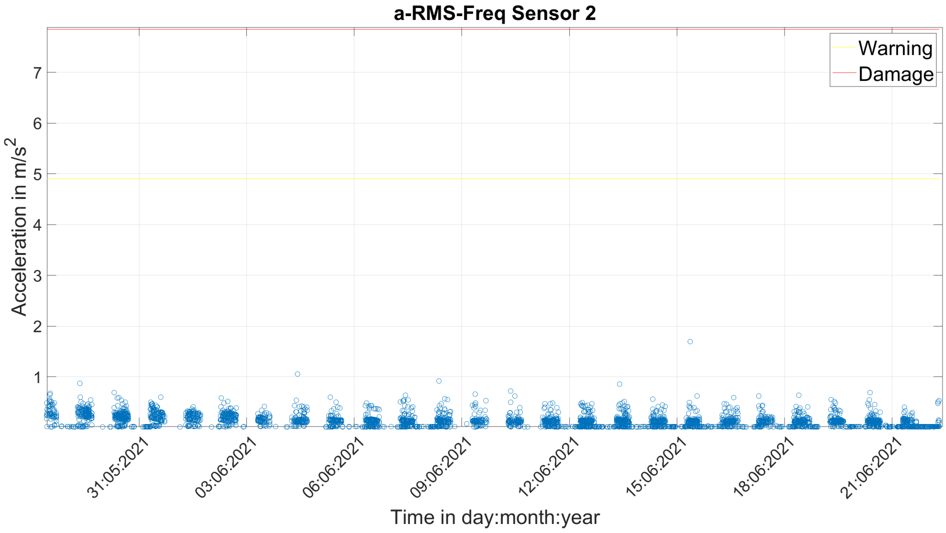

Figure 27

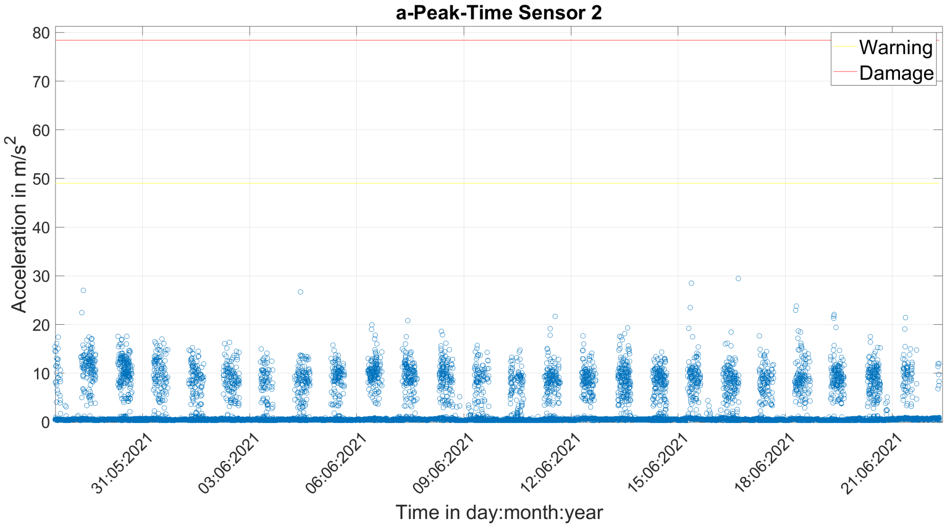

Figure 28

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