A uniform process for the implementation of Predictive Maintenance at BAM

MSc Master Thesis

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Colophon

Preface

Summary

Traditionally, maintenance is executed based on pre-determined moments or when problems arise (reactive maintenance). This can often result in problems with maintaining the reliability and availability requirements (uptime) of assets. In recent years, predictive maintenance (PdM) has become more relevant due to the technological developments of artificial intelligence (AI) and machine learning (ML). PdM can be used to reduce downtime, increase asset reliability, and decrease maintenance costs. BAM encounters problems with maintaining the contractually agreed availability requirements (uptime) on Schiphol for assets such as elevators, escalators, and moving walkways. These problems arise because the majority of the assets are older assets which have exceeded the end of life, resulting in high downtimes, low asset reliability, and high maintenance costs. To solve these problems and to guarantee the availability requirements (uptime) of these assets, BAM strives to implement PdM. However, so far they have encountered problems implementing PdM. The main problem is the lack of a uniform PdM process that can be used for the implementation.

The goal of this research was to develop a uniform predictive maintenance process for BAM. Therefore, the following research question was formulated: *"How can PdM be implemented for assets such as walkways, escalators, and elevators based on a uniform PdM process to decrease downtime, increase asset reliability, and decrease maintenance costs?"*. PdM is hereby defined as the process of using condition monitoring data to estimate the future condition of the asset. This process aims to predict when, where, and which assets may have potential failures (Schmidt & Wang, 2018).

In order to answer the research question, the research was divided into three phases, which included a literature review, interviews, document analysis, validation workshops, and a case study. The first phase was focused on developing a conceptual PdM process based only on literature gathered through the literature review. The second phase focused on gathering information about the current maintenance process and the feasibility of PdM for BAM through interviews. The third phase focused on transforming the current maintenance process into a new PdM process by means of the conceptual PdM process developed in the first phase. Additionally, the new PdM process was validated with validation workshops, a guideline was developed, and a case study was conducted to support BAM with the implementation of PdM.

The first part of the literature review resulted in a conceptual PdM process consisting of seven main phases. These main phases were elaborated in the literature review with activities to form the conceptual PdM process. The conceptual PdM process consists of seven subsequent phases: (1) determine failure mechanisms, (2) data collection, (3) pre-process data, (4) pre-analyse data, (5) model development, (6) analyse data, and (7) continuous monitoring and feedback loop. This process was used to develop, in combination with the current maintenance process, a new PdM process. Therefore, the current maintenance process had to be identified. However, it was first determined to what extent PdM was suited for BAM.

Based on interviews it was concluded that PdM is feasible for various assets on Schiphol and that, with a few adjustments, the organisation of BAM is suited for the implementation of PdM. Critical assets with various moving components such as elevators are very suitable for the implementation of PdM. Here, the feasibility was divided into technical and cost-benefit feasibility. The technical feasibility is determined by the amount of movable and/or electrical components, if the asset has failure mechanisms type A, B, C, D, E, or F as identified by the RCM cycles, and if the asset has failure mechanisms that can be predicted by collecting and analysing static and dynamic asset data. The cost-benefit feasibility is a balance between performance, risks, and costs. Most of the assets on Schiphol are technical feasible. However, not all assets are cost-benefit feasible. The needed adjustments to

make BAM suited for the implementation of PdM are related to the gathering and processing of data. BAM must prepare by gathering knowledge, hiring new employees to increase the capacity, and by training the current employees. In general, the organisation of BAM is, with some adjustments, suited for the implementation of PdM. However, to gather insight into the extent of the necessary adjustments, the current maintenance process was identified.

The current maintenance process consists of pre-defined maintenance actions that are based on static asset data. This conclusion was drawn from various interviews and conversations within the maintenance department. The current maintenance process consists of seven phases. The phases in subsequent order are (1) project transfer, (2) maintenance policy, (3) data collection, (4) data analysis, (5) maintenance preparation, (6) maintenance management, and (7) continuous monitoring and feedback loop. With the current maintenance process identified, it was possible to transform this process into a new PdM process. However, to develop a process that fits with the organisation of BAM, the desires from BAM needed to be processed into the new PdM process. Therefore, design requirements were identified in collaboration with BAM and ASM.

Based on interviews with employees from BAM and ASM (client) an extensive list of requirements was identified. This list was shortened to eighteen important design requirements based on the relevance for the PdM process. Additionally, the requirements were divided into must-have and nice-to-have requirements. The requirements were processed into a design brief and were used afterwards to integrate the conceptual PdM process with the current maintenance process to develop a new PdM process.

The new PdM process consists of the ten subsequent phases (1) project transfer, (2) maintenance policy, (3) data collection, (4) pre-process data, (5) pre-analyse data, (6) model development, (7) model verification, (8) analyse data, (9) maintenance management, and (10) continuous monitoring and feedback loop. The PdM process enables BAM to predict maintenance actions based on static and dynamic asset data. The main differences compared to the current maintenance process are the addition of dynamic asset data, the need for a new storage system, and the switch to predicting maintenance actions instead of pre-defined maintenance moments. Additionally, the fast amount of data provides an opportunity for an additional phase related to the development and verification of ML models to automate the determination of maintenance actions. Furthermore, the increased need for data processing results in the need for a data analyst and the increased complexity of the maintenance process increased the need for clear and uniform guidelines.

Based on the new PdM process a guideline was developed as a tool, including inputs and outputs of all phases, to increase the ease of implementation. The guideline was developed based on the PdM process and based on the validation workshops that were used to validate the PdM process. Additionally, a case study was executed to provide BAM with an example on how to determine data collection methods for dynamic asset data. The case study was executed because the validation workshops resulted in the conclusion that BAM does not have the necessary dynamic asset data and is unaware on how to gather this data.

The main objective of this research was to develop a uniform process for the implementation of PdM. During this research, a PdM process consisting of ten phases was developed. This process was validated through validation workshops. Additionally, a guideline and a case study were developed to improve the ease of implementing PdM. Due to the nature of the research, there are a few general recommendations and some recommendations related to future research.

The general recommendations are related to the collection and processing of data, the standardization of maintenance processes, and preparing the organization for the implementation of PdM. The recommendations related to future research are further conducting the case study, changing the maintenance of assets, and analyzing if the PdM process must be changed per discipline.

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Abbreviations

AI	=	Artificial intelligence
ASM	=	Asset management / Asset continuity
FMECA	=	Failure mode, effects, and criticality analysis
ML	=	Machine learning
MYMPs	=	Multiple Year Maintenance Plans
PdM	=	Predictive maintenance
RASCI	=	Responsible, Accountable, Supportive, Consulted, and Informed

Chapter 1

Introduction

1. Introduction

Transportation assets such as moving walkways, escalators, and elevators are critical assets of the transportation network on Schiphol. These assets are essential for an efficient and safe passenger flow and airport operation logistics. Ensuring that these assets are operating efficiently through frequent maintenance is essential to guarantee safe and reliable assets. In recent years PdM has become more relevant with the development of AI and ML (Canito, Corchado, & Marreiros, 2022). This arises from a desire to move from a reactive maintenance approach to a proactive approach. PdM can reduce downtime, increase asset reliability, and decrease maintenance costs. Additionally, PdM can be used to reduce maintenance activities and reduce the occurrence of malfunctions (Sresakoolchai & Kaewunruen, 2023). However, PdM needs a fast amount of accurate and reliable data, making it difficult to implement.

1.1 Problem definition

Traditionally, maintenance is performed as a reactive approach, problems are solved after they arise. PdM is a proactive and predictive method that has gained more momentum in the last few years (Canito, Corchado, & Marreiros, 2022). In combination with innovative technologies, reliable and accurate asset data can be gathered and processed for PdM.

BAM has the ambition to implement PdM for the assets on Schiphol. BAM Bouw en Techniek Schiphol Services is part of the larger company called 'Koninklijke BAM Groep'. BAM is responsible for all the assets within lot 5B which consists of Terminal 3, Schiphol Plaza, and all operation buildings located on and around the Airport. Many of the assets are older assets resulting in high downtimes, low asset reliability, and high maintenance costs. Asset downtime is caused by technical and non-technical issues such as molestation or user errors. Currently, BAM applies a combination of pre-defined maintenance based on schedules in accordance with the agreements and reports and reactive maintenance. BAM encounters various problems with the implementation of PdM that can be traced to the lack of a uniform PdM process that can be followed to implement PdM.

1.2 Research specification

Given the problem that a general PdM process for the implementation of PdM is not available in the construction industry, this research focused on analysing the PdM process to develop a uniform process for BAM. Therefore, the research objective reads: To develop a uniform PdM process for BAM. The developed uniform process can allow BAM to apply PdM for various important assets and thereby, decreasing downtime, increasing asset reliability, and decreasing maintenance costs.

To achieve the research objective the following main research question was formulated: "*How can PdM be implemented for assets such as walkways, escalators, and elevators based on a uniform PdM process to decrease downtime, increase asset reliability, and decrease maintenance costs?"*

Based on the engineering design cycle of Wieringa (2014) this research question was divided into the following three sub-research questions:

1. "*To what extent is PdM suited for BAM?"*.
2. "*What is the current maintenance process of BAM?"*
3. *"How can the current maintenance process of BAM be transformed into a process suited for the implementation of PdM?"*

1.3 Methodology

The research consists of four parts (Figure 1) originating from the research questions. The first part of the research is the theoretical research. This part consists of the theoretical framework consisting of a literature review. The goal of this phase was to develop a conceptual PdM process based on literature. The second part, the qualitative research, consists of interviews. The interviews were used to determine to what extent PdM is suited for BAM and to identify the structure of the current maintenance process. In the third part, the design & development PdM process, the conceptual PdM process and the current maintenance process were compared, with the goal to develop a new PdM process that fits as well as possible with the current maintenance process. Furthermore, the document analysis, the validation workshops, and the case study were conducted. The validation workshops were used for the validation of the PdM process whereas the document analysis was used to improve the developed PdM process. Additionally, a guideline was developed and a case study was conducted during this phase. The guideline was developed as a tool for BAM to ease the implementation of PdM. The case study was conducted to provide BAM with an example on how to determine the data gathering for elevators for the implementation of PdM. The last phase, the research report, consists of writing the report and processing the received feedback.

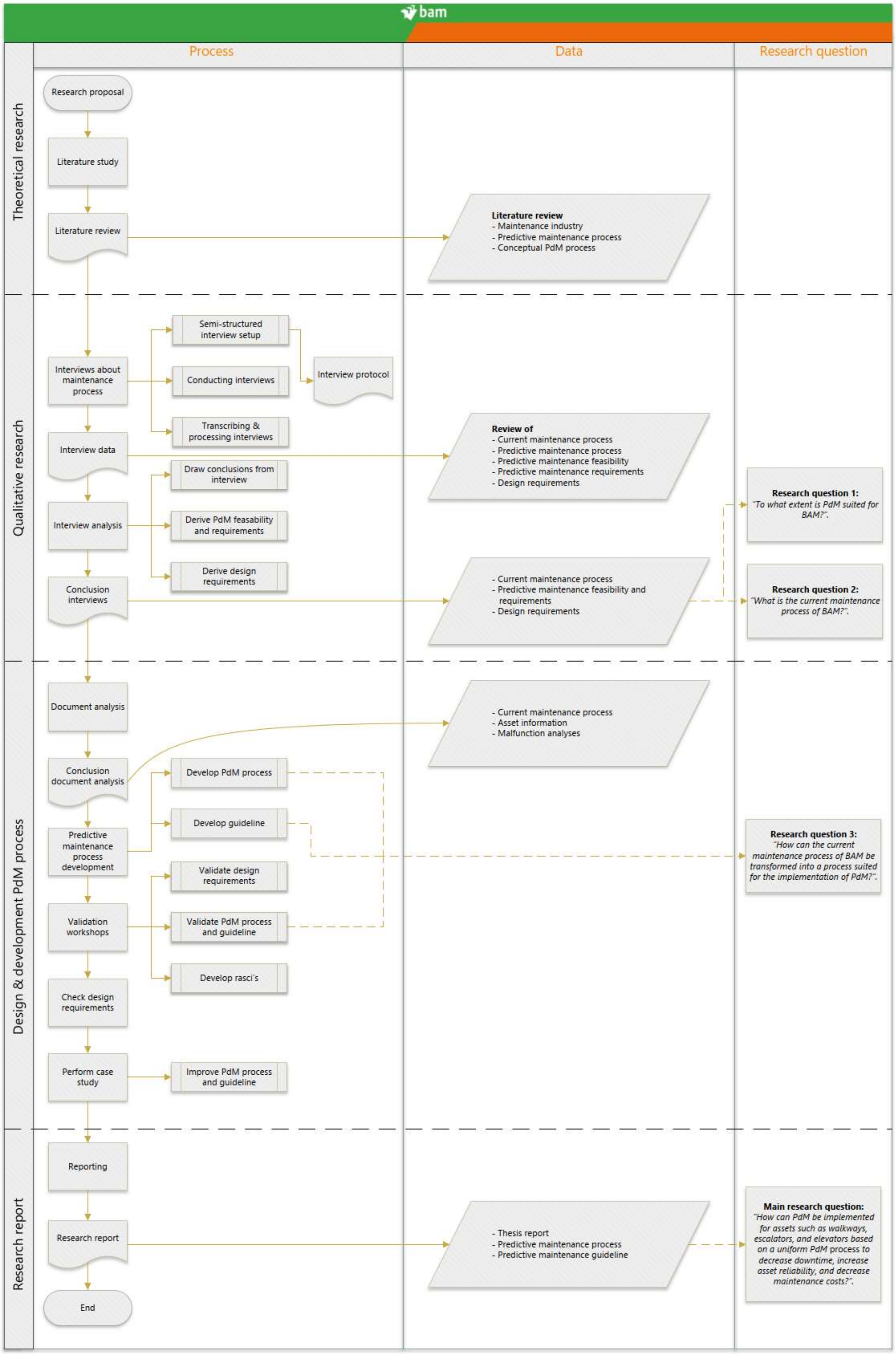

Figure 1 Research method flowchart

Literature review

In this research, the integrative literature review was applied, mainly because this method includes primary research studies and other documents such as policy documents, opinions, and discussion papers (Lubbe, Ham-Baloyi, & Smit, 2020). The result of the integrative literature review was the synthesis of the gathered data, in the way of alternative processes or conceptual frameworks (Torraco, 2005). In this research, the alternative process is a process developed based on the literature review explained in Chapter 2. The search terms used to gather the literature are visualized in Appendix I – Literature review protocol.

Interviews

Interviews were used to determine to what extent PdM is suited for BAM (Research Question 1) and to gather insight into the current maintenance process of BAM (Research Question 2). Furthermore, interviews were used to determine the design requirements of BAM and ASM for the PdM process.

The interviews were conducted with employees from BAM and ASM to answer the first and second research questions. ASM is responsible for the development and realization of projects on Schiphol. Fifteen interviews with twelve distinct roles were conducted (Figure 2). The interviewed employees were carefully selected based on (1) their role within the company, (2) their hierarchical level in the company, and (3) their knowledge of PdM or the current maintenance approach. The employees of BAM are indicated as BAM, and the employee of ASM is indicated as ASM.

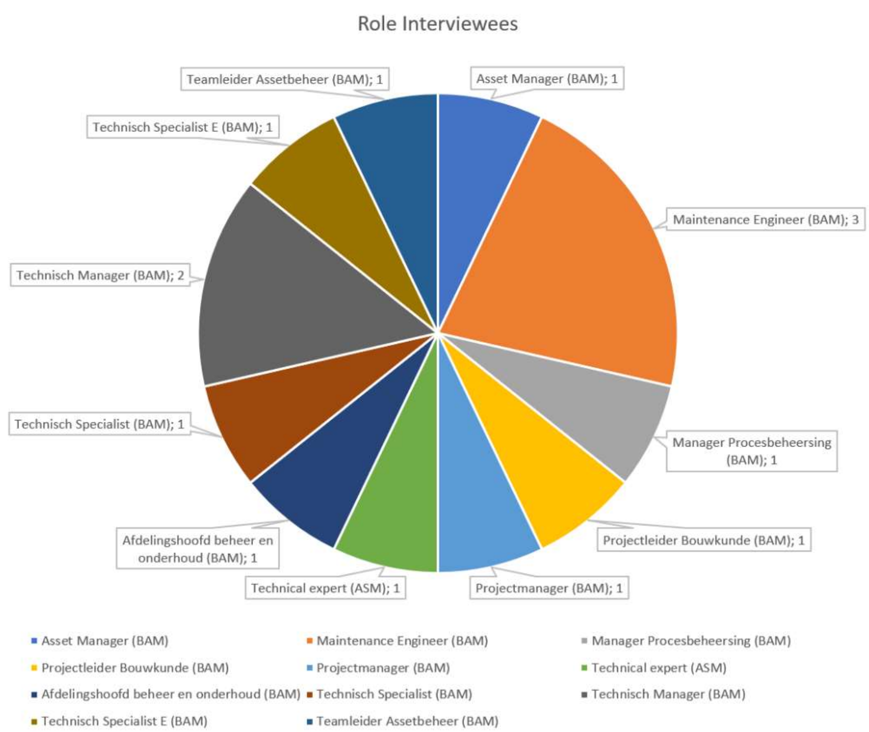

Figure 2 Role Interviewees

In order to guarantee that all data was gathered, interview questions were drawn up in the interview protocol (Appendix II – Interview protocol). Furthermore, the interview protocol explains how the interviews are conducted. The questions were divided into six categories: (1) general, (2) maintenance knowledge, (3) process, (4) customer, (5) data, and (6) BIM. Depending on the role and corresponding knowledge of the interviewees, one or multiple of these categories were included in the interview. The interviews were transcribed in order to analyse the data.

The transcribed interviews were analysed by colour-coding the answers of interviewees corresponding with certain subjects (Appendix V – Interviews). The analysed subjects are:

- Design requirements
- Requirements PdM
- Asset suitability PdM
- Advantages PdM
- Challenges, risks, and/or problems of PdM
- Reliability data
- Process implementation

Each interview had a duration of 30 to 90 minutes and was conducted in the form of semi-structured interviews as recommended by Hansen (2021) when dealing with small sample sizes. Semi-structured interviews provided the researcher with flexibility in asking different questions based on the interviewee's answers, allowing for innovative ideas and insights (Hansen, 2021). The exact time consumption of the interviews was based on the amount of information the interviewees could provide about the (predictive) maintenance process and desired design requirements.

Document analysis

The document analysis was used to support the previously mentioned data collection methods. Hence, this method was used to answer Research Question 1, Research Question 2, and Research Question 3. According to Bowen (2009), document analysis is the process of systematically reviewing or evaluating documents. The document analysis was performed to gather more insight into the PdM process to further develop the conceptual process. Additionally, the analysis was conducted to gather insights into the maintenance process currently applied by BAM.

Workshops

Two workshops were held with employees of BAM to validate the developed PdM process and to develop part of the guideline. The first workshop was held to validate the design requirements, the PdM process, and to develop RASCIs for the steps included in the PdM guideline. This workshop was therefore a combination of a validation workshop and a brainstorming workshop. The second workshop was used to validate the adjusted design requirements and the adjusted PdM process. In order to derive as much information as possible from the workshops, workshop protocols were developed (Appendix III – workshop protocol). The size of the workshops existed out of six employees of BAM who were selected based on their knowledge of the current maintenance process and the PdM process. Therefore, the following functions were selected:

- Asset manager
- Maintenance engineer
- Manager process control
- Technical manager
- Technical specialist E
- Teamleader asset maintenance

Case study

The case study was used to explain how the guideline can be used by BAM to implement PdM. Specifically, the case study was conducted to provide BAM with an example on how to determine and collect the necessary data for the implementation of PdM. This decision was made because the validation workshops resulted in the conclusion that the necessary data is not present and that BAM is unaware of how to gather this data. The case study was conducted for elevator 53. This elevator was selected because the availability requirement (uptime) of this elevator is lower than all other elevators. The case study was conducted by implementing the first three phases of the guideline. In order to conduct the case study, expert knowledge from one of the maintenance engineers of BAM was used. In cooperation with the maintenance engineer, the case study was conducted to provide an example on determining the necessary data for the implementation of PdM.

1.4 Research scope

To provide BAM with information about the implementation of PdM a uniform PdM process was developed. The PdM process was developed to a depth of multiple activities per phase explanation. The process can be used to implement PdM. Hence, this process explains how the phases are structured but does not provide specific solutions. This is for the reason that the developed process is made uniform to be able to use it for more assets. At the end of the research, a guideline was developed and a case study was conducted to make the implementation of PdM less difficult.

1.5 Expected results

The expected results of this research were fourfold. Firstly, a literature review upon the PdM process was provided. Here, a clear overview of the theoretical process was given including a conceptual PdM process. This process was used in combination with the current maintenance process to develop the new PdM process for BAM. The literature review can be found in Chapter 2.

In the second part, interviews were conducted to gather information about the current maintenance process, considerations for PdM, and design requirements for the new PdM process. The PdM consideration can be found in Chapter 3, followed by the current maintenance method in Chapter 4 and the derived design requirements in Chapter 5.

In the third part, the current maintenance process (Chapter 4) was transformed into a new PdM process (Chapter 6) by the use of the conceptual PdM process (Chapter 2). Based on the new PdM process a guideline was developed to provide a tool for the implementation of PdM. The developed guideline can be found in Chapter 8.

In the last part, the new PdM process was validated through validation workshops and validation of the design requirements. Furthermore, a case study was conducted to provide BAM with an example of the implementation of PdM. The design requirements can be found in Chapter 7. The case study can be found in Chapter 9.

Chapter 2

State-of-the-art PdM

2. State-of-the-art PdM

2.1 Maintenance strategies

Maintenance is a combination of technical, managerial, and administrative actions needed to retain or restore the asset to a state where it can perform the desired function during the entire lifecycle. Based on the EN 13306 maintenance can be divided, as visualized in Figure 3, into corrective maintenance and preventive maintenance (Schmidt & Wang, 2018).

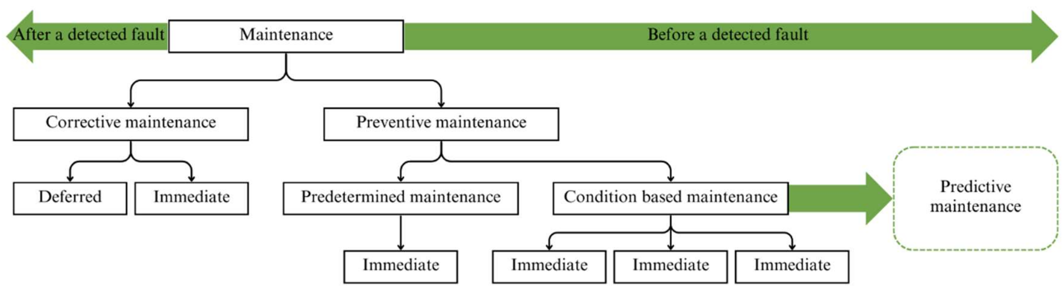

Figure 3 Structure of maintenance strategies (Schmidt & Wang, 2018)

Corrective maintenance is the process of performing maintenance after the asset has failed (Bouabdallaoui, Lafhaj, Yim, Ducoulombier, & Bennadji, 2021). This approach is based on reactive maintenance. Preventive maintenance is the process of performing inspections and maintenance before the asset has failed. In general, the inspections are performed on a time-based or usage-based schedule. This approach still results in unplanned failures (Bouabdallaoui, Lafhaj, Yim, Ducoulombier, & Bennadji, 2021). Condition-based maintenance is a form of preventive maintenance where historical and current data is used to determine maintenance actions (Krupitzer, et al., 2020). Condition-based maintenance only allows maintenance engineers to predict failures on narrow future periods when the measured values crossed the developed thresholds. Hence, condition-based maintenance cannot isolated be seen as PdM (Krupitzer, et al., 2020).

PdM is the process of using condition monitoring data to estimate the future condition of the asset. This process aims to predict when, where, and which assets may have potential failures (Schmidt & Wang, 2018). This process includes condition monitoring, fault diagnosis, and maintenance management (Zhong, Xia, Zhu, & Duan, 2023).

2.2 PdM

PdM uses current and historical data to predict the future state of the asset for longer periods in the future (Motaghare, Pillai, & Ramachandran, 2018). Here, a difference is made between fault diagnosis (short-term) and fault prognosis (long-term). The summarized process of PdM is visualized in Figure 4.

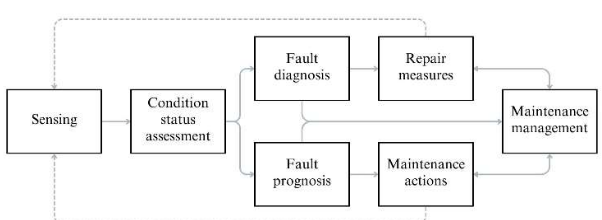

Figure 4 PdM process flow, based on (Standardization Council Industrie 4.0, 2018)

According to Yongyi et al. (2019), PdM is a suitable application if the failure modes of the asset can cost-effectively be predicted based on regular monitoring. The benefits of this maintenance method are (1) a holistic view of equipment health, (2) improved analytics options, (3) avoidance of running to failures, and (4) avoidance of replacing a component with a remaining useful life (Yongyi, Xin, Pengfeng, Yonggang, & Ruilong, 2019). However, this method has disadvantages that prevent the method from implementation on a large scale in the construction industry such as (1) high equipment costs for condition monitoring, (2) high needed skill level and experience for interpretation of condition monitoring data, and (3) high upfront cost of condition monitoring (Wang, Li, Braaten, & Yu, 2015).

2.3 PdM conceptual process

Various authors explain the PdM process as various subsequent phases. Sang et al. (2021), generalized the process of PdM into three phases: data acquisition, data process & prediction, and maintenance decision support. Whereas Wang (2021) developed the process of PdM as data acquisition and processing, state identification, fault identification and location, health prediction, maintenance management, and maintenance execution. Other authors such as Kamel (2022) and Ahmer et al. (2022) agree with this process with adjustments in the terms of the phases. The most extended process is developed by Bouabdallaoui et al (Bouabdallaoui, Lafhaj, Yim, Ducoulombier, & Bennadji, 2021). Here, the main phases of the process exist out of data collection, data processing, model development, model deployment, and feedback and process improvement. In this research, the phases of the various authors are merged and slightly altered resulting in the following seven phases: (1) determine failure mechanisms, (2) data collection, (3) pre-process data, (4) pre-analyse data, (5) model development, (6) analyse data, and (7) continuous feedback and monitoring. Based on the literature review the phases are further elaborated in activities forming the conceptual PdM process visualized in Figure 5. The conceptual PdM process is also added in Appendix IV – conceptual PdM process.

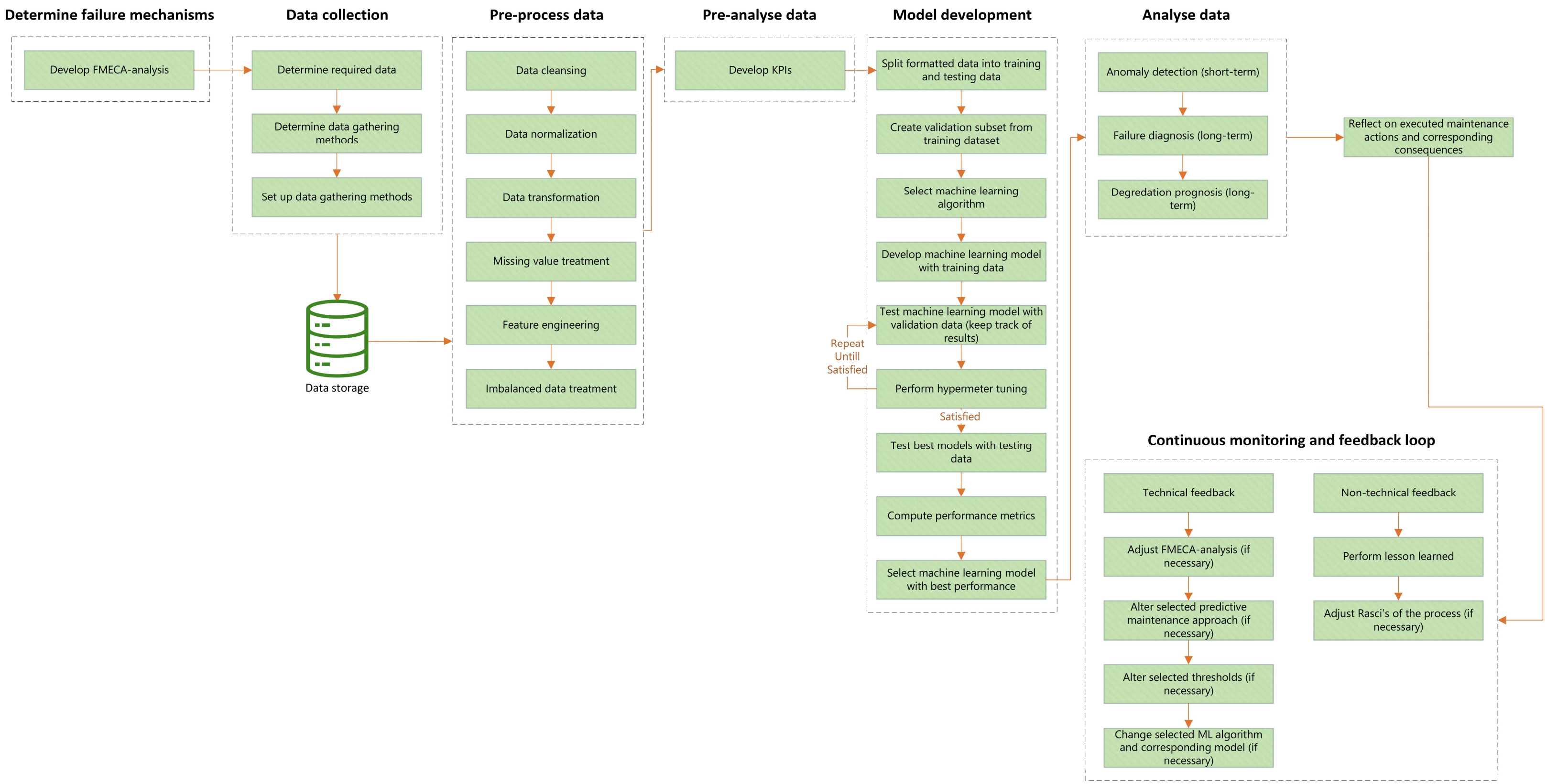

Figure 5 Conceptual PdM process

Determine failure mechanisms

Failure mechanisms can be identified through various tools each with pros and cons. Often used tools are FMECA's, fault tree analysis, and event tree analysis. Fault tree analysis is the least extended tool. With this tool failure mechanisms are identified without including risks and consequence calculation. Event tree analysis is a little more extended. Here, probabilities (risks) are identified for the failure mechanisms. FMECA's are the most comprehensive and complex tool available and therefore most often applied (Spreafico, Russo, & Rizzi, 2017). With this tool failure mechanisms are identified, probabilities are calculated, and the consequences are determined. Hence, in the conceptual PdM process, FMECA's are included.

Data collection

In the introduction of this chapter, the definition of PdM was stated as: *"PdM is the process of using condition monitoring data to estimate the future condition of the asset. This process aims to predict when, where, and which assets may have potential failures"*. This definition states only one data source (**condition monitoring data**). However, for accurate PdM more data types are needed. Tinga & Loendersloot (2019) extended this definition by including data sources such as **load/usage data**, **sensor data**, and **stressor data**. These four data types have overlap between them. Hence, in this research, the data types are slightly altered. The used data types are condition data, sensor monitoring, and stressor monitoring. The **condition data** is related to all information on the condition of the asset (e.g., inspection data). The **sensor monitoring** data is related to all data gathered from the asset including sensor data and usage data. The **stressor data** is related to all data gathered from the environment of the asset, in other words, external data. The three data types can be gathered in several ways.

Sensor data has several possibilities dependent on the needed data such as force, acoustic emission, balancing unit, power, strain, vibration (Ahmer, Marklund, Gustafsson, & Berglund, 2022), humidity, ambient temperature, ambient pressure, acoustic signal, thermography, motor current, insulation resistance, electrical capacitance, and electrical inductance (Hashemian & Bean, 2011). According to Coanda et al. (2020), many of these aspects can be measured with vibration analysis, acoustic analysis, lubrication oil analysis, particle analysis, corrosive analysis, thermal analysis, and performance analysis. Stressor data can be collected with similar methods as sensor data. The difference between these data types is that sensor data is asset-related (intern), and stressor data is environmental-related (extern).

The types and amount of data are determined by the asset type and by the decision on how extended PdM is applied. Often applied PdM methods are 'reliability statistics-based', 'experience-based', 'sensor-based', 'degradation-based', and 'model-based' (Tinga & Loendersloot, 2019).

Careful data handling is needed to deal with noise, outliers, and missing data (Nunes, Santos, & Rocha, 2023). Additionally, the quality of data influences the possibilities and quality of the PdM process. According to Bekar et al. (2020), the quality of the data can be evaluated based on six dimensions visualized in Table 1.

Table 1 Description of data quality dimensions (Bekar, Nyqvist, & Skoogh, 2020)

Data quality dimension	Description
Accuracy	Data is without errors and data is correct and reliable.
Completeness	No missing necessary data and the data includes the expected data value range.
Timeliness	Data is up to date.

Consistent representation	Data is available in corresponding formats.
Accessibility	Data is available or easy and quickly retrievable.
Relevancy	Data is applicable and helpful.

Data storage

Data storage is particularly important for the huge amount of data that must be collected, stored, and processed for the PdM process. On a technical level, there are various solutions to achieve the collection, storage, and processing of data. The solution for data storage is currently being researched by BAM. Therefore, this matter goes beyond the scope of this research. However, below several crucial factors of the data are explained. According to Xin & Ling (2013), the most notable features of the data are the "4Vs" (volume, velocity, variety, and value).

Volume is increasing drastically with the desire for PdM. The huge volume of data originating from various sources results in the need for large data storage capacity, and faster data transferring and processing speed. With the use of automatic data retrieval systems, the data velocity can be increased to enable real-time information from various sources. With the development of various analytic processes, it is possible to process different data types than just numerical results thereby increasing the variety of data. Combining the different data from various sources increases the value of data (Lee, Cao, & Ng, 2016). Combining and visualizing this data can, among others, be done with digital twins (Cavalieri & Salafia, 2020).

Digital twin is a technology that can virtually represent physical objects, processes, and real-time data (Wu, Yang, Cheng, Zuo, & Cheng, 2020). Digital twin allows engineers to monitor, share, and visualize information needed to optimize the construction and maintenance of assets (Kaewunruen, AbdelHadi, Kongpuang, Pansuk, & Remennikov, 2023). Digital twin is a tool that stems from an integration of technology in the architecture, engineering, and construction (AEC) industry in recent years (Rafsanjani & Nabizadeh, 2023). In terms of asset management digital twins can be created by combining data from various sources such as historic data, BIM scans, sensors, and maintenance records (Divya, Marath, & Santosh Kumar, 2023). Digital twins can be used to gain a better understanding of transportation assets and to predict maintenance in order to reduce downtime, increase asset reliability, and decrease maintenance costs (Sresakoolchai & Kaewunruen, 2023).

Pre-processing data

Careful data handling is needed to deal with noise, outliers, and missing data (Nunes, Santos, & Rocha, 2023). The method of handling these aspects is described as pre-processing of data by most authors (Cernuda, 2019). Cernuda (2019), developed a taxonomy for the pre-processing of data for the use in the training of a ML model. This process includes six steps: (1) data cleansing, (2) data normalization, (3) data transformation, (4) missing values treatment, (5) feature engineering, and (6) imbalanced data treatment (Cernuda, 2019). The pre-processing steps are explained in Table 2.

Table 2 Pre-processing data steps

Steps	What	Why
Data cleansing	Process of cleansing the data by dealing with aspects such as noise, outliers, irrelevancy, and redundancy.	Reliable, complete, and noise-free data is often required for data-driven techniques.
Data normalization	Process of normalizing the data by removing the variety of scales and ranges of variables originating from various sources.	Some algorithms are extremely sensitive to varying scales and ranges resulting in a decrease in the performance.
Data transformation	Process of converting data into a different format.	Necessary to combine the data from various sources as input for tools such as ML models.
Missing values treatment	Process of dealing with missing value due to various causes.	Necessary to guarantee reliable and accurate datasets.
Feature engineering	Process of selecting features, extracting features, and discretization features.	Increase the reliability of the outcomes.
Imbalanced data treatment	Process of balancing data because a certain data type is rare compared to another type.	Prevent unreliable and inaccurate results from unbalanced data.

Pre-analyse data

KPIs are often used to determine when actions must be undertaken (Cinar, Kalay, & Saricicek, 2022). Maintenance actions are executed to guarantee that the values remain above or below the developed KPIs (Yongyi, Xin, Pengfeng, Yonggang, & Ruilong, 2019). The combination of the data and the KPIs result in asset failure identification, performance degradation evaluations, and maintenance schedule optimization (Li, Wang, & Wang, 2017). The possible KPIs are based on the specific asset that is monitored.

The selected KPIs and analysis are based on the failure modes of the asset. Therefore, it is important to first analyse the possible failure modes of the asset to determine the appropriate KPIs (Ahmer, Marklund, Gustafsson, & Berglund, 2022). KPIs can be integrated with ML models.

ML models can be trained to identify when data crosses predefined KPIs (Amaral, Laadjal, & Cardoso, 2023). Additionally, ML models can be trained, based on various data, to predict when the KPIs are crossed in the future. These KPIs can be supported or extended with KPIs prescribed by the manufacturer (Shaheen, Kocsis, & Németh, 2023).

Model development

The main part of the PdM process is gathering and analysing data to perform fault detection and predict future failures (Oudenhoven, Calseyde, Basten, & Demerouti, 2022). Hence, algorithms are needed to analyse this data to predict future asset quality. Authors often use various algorithms such as model-based algorithms, artificial neural networks, and support vector Machines (Yongyi, Xin, Pengfeng, Yonggang, & Ruilong, 2019).

There are numerous approaches to developing a ML model, each with its pros and cons. However, most of the approaches are based on similar phases (Figure 6). Developing a ML model starts with splitting the data into training and testing data.

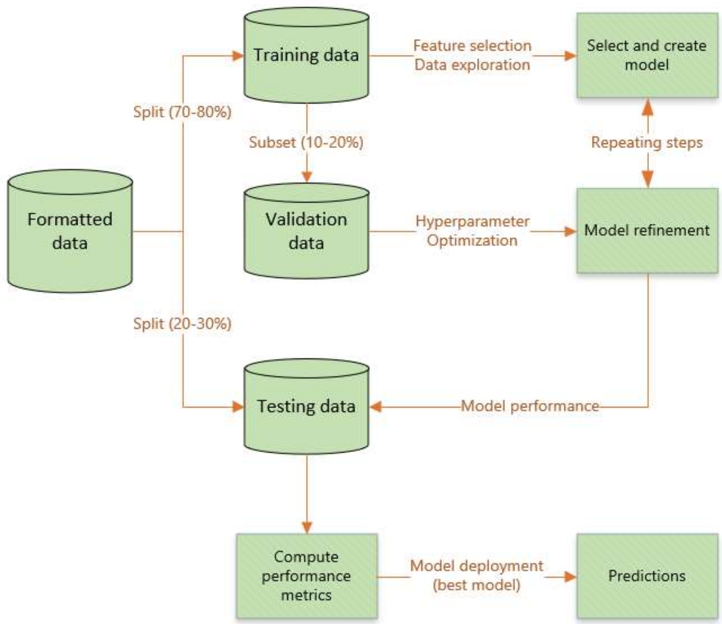

Figure 6 ML model development process, based on (Pruneski, et al., 2022)

The **training data** is used to train the algorithm to recognize certain patterns whereas the **testing data** is used to validate the performance of the developed ML model. The distribution between training and testing data is dependent on the quantity and quality of the data. However, in most cases, a distribution of 70-80% training data is used to train the model. The remaining data is used to validate the model. Here, it is important that the model has not yet seen/analysed the testing data before validation of the model. Otherwise, the model has already learned from the testing data resulting in the fact that the model cannot be validated with this data. Within the training data, a subset of 10-20% is taken to use as finetuning and validation of the model during the development phase (Pruneski, et al., 2022).

Splitting of data can be performed through various approaches such as 'simple splitting'. This method is often used because it leads to low bias and high variance in the data. Within this method, the probability of selection of the samples are all equal. Hence, the name simple splitting. With the split training data, the next step is selecting the ML algorithm followed by the development of the ML model (Pruneski, et al., 2022).

As mentioned before there are numerous ML algorithms and models. However, in general, three types of models can be identified; (1) supervised, (2) unsupervised, and (3) semi-supervised (Bhat, Muench, & Roellig, 2023). The innovations within ML and AI move rapidly. Hence, it is not possible to advise a singular ML model. At the moment of implementation of PdM a ML model must be selected based on all available models. The split testing data can be used to assess the accuracy of the model. The results from this test are used to compute the performance metrics of the models to select the best model for use during the implementation of PdM.

Analyse data

With the ML model developed, the analyse data phase of the PdM process can start. The ML model is used to determine the needed maintenance. During the analyse data phase the necessary maintenance actions are determined. Hence, during this phase, the model is used to analyse the available data to determine the maintenance actions.

Analysing the data to derive maintenance actions of the PdM process can be performed in three steps as identified by Serradilla et al. (2022). The three steps are (1) anomaly detection, (2) failure diagnosis, and (3) degradation prognosis. Serradilla et al. (2022), also identified a fourth step; mitigation. However, in this research, the mitigation step is not used because the risks are mitigated by executing the determined maintenance actions.

Anomaly detection is the first step and is used to detect if the asset under normal conditions is performing as intended. The second step; failure diagnosis starts after the anomaly is detected. In this step is determined if the anomaly can result in a failure. The third step; degradation prognosis starts after the anomaly is detected and a failure mechanism is diagnosed. In this step, a prognosis of the degradation of the asset is made based on current working conditions and future expected conditions. This prognosis is often delivered as the remaining useful life (RUL).

The three steps included in this phase are used to determine maintenance actions that must be executed. First, data is analysed to identify anomalies. These anomalies can in the future result in malfunctions that must be solved. The identified anomalies are further researched to diagnose failure mechanisms. Based on these failure mechanisms additional maintenance actions are determined. Furthermore, based on the possible maintenance actions a degradation prognosis is developed for various scenarios with different maintenance actions. The degradation prognosis can be used to determine the best maintenance actions at the most suited moments.

Continuous feedback and monitoring

With the implementation of PdM, continuous improvement must take place (Pejić Bach, Topalović, Krstić, & Ivec, 2023). Hence, feedback loops are implemented in the process to guarantee continuous improvement. One example of the feedback loop is the continuous improvement of the ML model. The ML model must be updated regularly with new training data, and new ML models must regularly be developed to maintain or exceed the performance of the previous process (Pruneski, et al., 2022).

Chapter 3

PdM consideration

3. PdM consideration

The goal of this research was to develop a uniform process that BAM can use to implement PdM for various assets. To achieve this goal first it had to be determined if PdM is suited for BAM. Thereby, this chapter answers research question 1; "*To what extent is PdM suited for BAM?*".

The answer to this research question is twofold. On the one hand, this question is related to the suitability of PdM for the assets in maintenance by BAM. On the other hand, the question is related to the suitability of PdM within the organisation and the current maintenance method of BAM. For the second part, the current maintenance process had to be identified (Chapter 4).

3.1 Asset suitability PdM

According to many different interviewees, the aspects that determine if assets are suited for PdM lie in two categories: the technical suitability and the cost-benefit suitability (Table 3). The technical suitability is determined by the fact if the asset includes components that can be measured with among others, sensors (Appendix V – Interview code IV), by the type of failure mechanism, and by the fact if the failure mechanisms can be predicted by data collection and analyses (Appendix V – Interview code I). The **type** of **failure mechanisms** is divided into types A, B, C, D, E, and F (Figure 7). According to maintenance engineers, failure mechanisms suited for PdM are mechanisms A, B, C, E, and F.

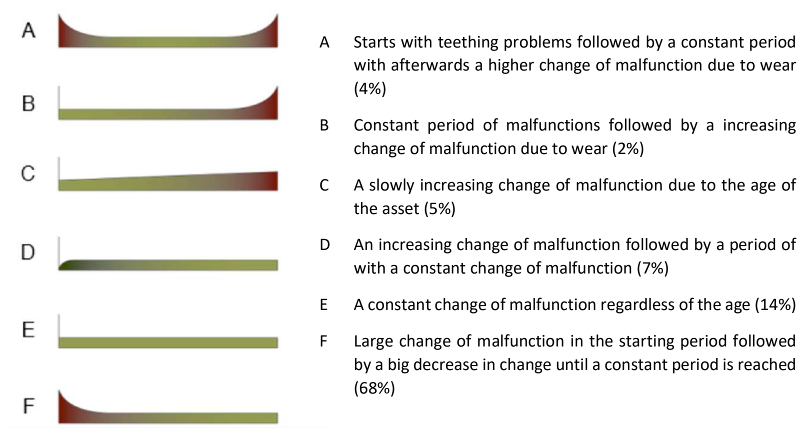

Figure 7 Type of failure mechanism including explanation, based on: Appendix VI – Document analysis code I

The cost-benefit suitability is based on the criticality of assets (Appendix V – Interview code VII), the amount of needed maintenance, and the possible cost reduction (Appendix V – Interview code III). Overall, the cost-benefit feasibility is a consideration between costs, performance, and risks (Appendix V – Interview code I). The feasibility is determined by both technical and cost-benefit feasibility. Assets must be technical feasible and cost-benefit feasible to implement PdM. For example, an electrical boiler is not suited for PdM because this asset is almost maintenance-free except for a replacement when the asset fails. This conclusion applies even though PdM is technical-wise feasible for electrical boilers (Appendix V – Interview code III).

Table 3 Feasibility of PdM

Feasibility	
Technical	**Cost-benefit**
Various measurable movable and/or electrical components.	Criticality of the asset (performance).
Type of failure mechanisms (A, B, C, E, or F).	Possible maintenance reduction (risks).
Failure mechanisms can be predicted by gathering data.	Possible cost reduction (costs).

To provide insight into the suited assets for the implementation of PdM an extensive list of assets in maintenance of BAM was analysed in cooperation with a maintenance engineer. In this analysis was determined if the assets are technical suited for the implementation of PdM and if implementing PdM has potential value. The cost-benefit feasibility is situation (case) specific and can be different for assets within similar asset types (e.g., elevator X may be suited whereas elevator Y may not be). Hence, it is not possible to provide the cost-benefit suitability for all asset types. The longlist of analysed assets can be found in Appendix VII – suited assets PdM. Table 4 provides a few assets that are/are not suited for the implementation of PdM.

Table 4 Suited and not suited assets for the implementation of PdM

Suited	Not suited
Elevators	Electrical boilers
Escalators	Collision protection
Moving walkways	Lights

Various interviewees stated that because of the amount of movable and electrical components and because of the criticality, the transport assets (e.g., elevators, escalators, moving walkways) are very suited for PdM (Appendix V – Interviews). The primary function on Schiphol is moving passengers from A to B, here the transport assets play a vital role. Hence, in combination with the number of components that can be measured the transport assets are very suited for PdM. Moreover, transport assets were mentioned as assets with the highest potential to implement PdM (Appendix V – Interview). However, this does not yet answer if PdM is suited to be integrated within the current maintenance method of BAM.

3.2 Organisation suitability PdM

It was difficult to conclude if the organisation is suited for the implementation without first integrating the conceptual PdM process with the current maintenance process. However, the goal of the first research question was to determine if PdM is suited for the general organisation of BAM. This question can be answered with data gathered from the interviews. From the interviews, it was concluded that the organisation of BAM is suited for the implementation of PdM with certain adjustments. The main adjustments needed for the implementation of PdM are the supply and processing of data needed for PdM. In order to apply these adjustments, the organisation of BAM must prepare by gathering knowledge, hiring new employees, and training employees with among others a strong vision on PdM. Here, it is important that is determined what skills, backgrounds or profiles are necessary for future employees to possess to support the implementation of PdM.

3.3 Conclusion

The first research question reads: *"To what extent is PdM suited for BAM?".* The answer to this research question is that PdM is suited for BAM to use for certain assets, especially critical assets with various moving components such as transportation assets (e.g., escalators, elevators, and moving walkways). This conclusion is based on the technical feasibility and the cost-benefit feasibility. The technical feasibility is determined by the amount of movable and/or electrical components and if the assets have failure mechanisms that can be predicted by collecting and analysing data from the assets. The cost-benefit feasibility is determined by a consideration of performance, risks, and costs. The overall feasibility of PdM is determined by the fact if it is technical feasible and if it is cost-benefit feasible. Most assets on Schiphol have a technical feasibility for the implementation of PdM. However, not all assets have a cost-benefit feasibility. Hence, it is not always advised to implement PdM even though it is technical feasible. PdM is suited to implement within the organisation of BAM by making certain adjustments. BAM can prepare the organisation for the implementation of PdM by gathering knowledge, hiring new employees, and training employees with among others a strong vision on PdM. It can be concluded that a balance between people, organisation (process), and technology is important for the implementation of PdM.

Chapter 4

Current maintenance process

4. Current maintenance process

The goal of this research was to develop a uniform process for BAM that is integrated with the current maintenance process as well as possible. Therefore, the current maintenance process was identified to answer the second research question; "*What is the current maintenance process of BAM?*". The current maintenance process (Figure 8) was identified through conversations held with various maintenance engineers. The current maintenance process is also added as Appendix VIII – Current maintenance process.

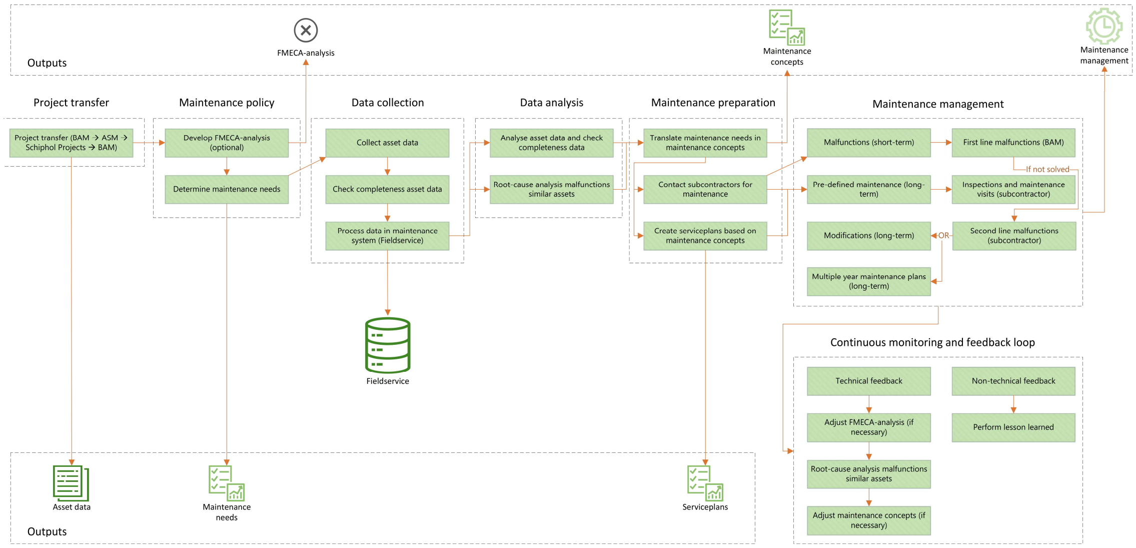

Figure 8 Current maintenance process BAM

The current maintenance process can start in three ways. The first is based on MYMPs. The MYMPs are proposed by the maintenance management department of BAM. The ASM department of Schiphol approves or adjusts these plans. Thereafter, the project is passed on to Schiphol Projects and then passed on again to the realisation department of BAM that starts the project. The second way is with an entire area that must be renovated. Within this project all assets are demolished and new assets are developed. The third way is with an asset needing new maintenance. For example, PdM is applied to an existing asset. Here, the project transfer is internal within the maintenance management department. The project transfer includes various asset data related to what, how and when the asset is built (**static data**). The asset management department must determine the maintenance policy for the asset. This can be done by, optionally, developing a FMECA-analysis for the asset. Based on standards, KPIs, regulations, requirements from Schiphol, and optional FMECA-analysis the **maintenance needs** are determined. The asset data received during the project transfer phase is collected, checked for completeness, if necessary supplemented, and processed into the maintenance system (Field Service).

The developed maintenance needs are translated into maintenance concepts. In the **maintenance concepts** is included how, what, and when maintenance is desired. The maintenance concepts are used to contact subcontractors for a price calculation for the maintenance. Parallel to this process serviceplans are created based on the maintenance concepts. The **serviceplans** are specific to the maintenance system (Field Service) and are a translation from the maintenance concepts to workorders. The **workorders** are used to execute the maintenance.

The maintenance management consists of four flows. The first flow; malfunctions is partly managed by BAM and partly managed by a subcontractor. BAM is the first line malfunctions, meaning that BAM attempts to solve malfunctions within a brief period when they arise. Dependent on the asset type and based on how acute the problem is for safety BAM has less than 15 minutes or less than an hour to secure the asset. BAM has less than 3 hours to restore the functionality of the assets and less than a day to develop a restoration plan. If BAM cannot solve the malfunctions within the given timeframe the malfunctions flow over to the second line malfunctions. Subcontractors execute the second line malfunctions. If it turns out that the subcontractors cannot solve the malfunction without changing the asset or replacing large parts of the asset, the malfunction is transferred into the modification flow (second flow) or the multiple year maintenance plans (third flow).

Modifications are non-functional changes of assets that do not exceed 125,000 euros. The modification flow is prepared by BAM, followed by either an execution by BAM or an execution by a subcontractor. The MYMPs are developed to maintain the quality of the asset. These plans include maintenance for multiple years and are developed based on the condition, age, and malfunctions of the asset. The last flow: pre-defined maintenance, is the general pre-defined maintenance included in the maintenance concepts.

The maintenance process visualized in Figure 8 is how BAM currently executes the maintenance process. However, BAM will be adjusting this process slightly in the coming months. Currently, the contract includes specific information about what type of maintenance is executed, how the maintenance is executed, and how the results are visualized towards BAM. However, the subcontractors do not always follow this contract and BAM does not always reflect if the subcontractor follows the contract. In the future, BAM will put more effort into guaranteeing that the subcontractor follows the contract. This adjustment does not change the flow of the current maintenance process and is therefore not included in the remaining part of this research.

By analysing the conceptual PdM process and the current maintenance process it was concluded that there are significant differences between the two processes. The main difference is the fact that in the PdM process, static and dynamic asset data are used, whereas in the current maintenance process, only static asset data is used. Furthermore, the dynamic asset data resulted in additional phases in the conceptual PdM process related to the processing of this data such as the pre-process data phase. Additionally, the conceptual PdM model includes the development of a ML model to derive maintenance actions based on the gathered data. Meanwhile, in the current maintenance process maintenance actions are manually determined based on expert knowledge and static data such as inspections. It can be concluded that the current maintenance process is highly dependent on expert knowledge for maintenance actions, whereas the conceptual PdM process is more dependent on expert knowledge for understanding the fast amount of collected and analysed data. Besides the difference, there are also some comparisons. The main comparison is that in both processes failure mechanisms are identified and various PDCA-cycles are included.

Chapter 5

Design requirements

5. Design requirement

The goal of this research was to develop a new process for BAM. Hence, the process must be in line with the expectations of BAM. Therefore, design requirements were gathered. The design requirements were gathered through analysing the data from interviews with BAM and ASM. Additionally, the design requirements were validated through two workshops.

5.1 Design brief

The maintenance process of the assets on Schiphol is a cooperation between BAM Bouw en Techniek B.V. and Schiphol Nederland B.V. Therefore, employees from these two companies were interviewed to gather design requirements for the PdM process. The interviews with employees from these two companies resulted in an extended list of twenty-nine design requirements (Appendix IX – Design requirements). Thirteen design requirements were derived from an interview with a technical expert from ASM (Appendix V – Interview Code VIII). The remaining design requirements were derived from interviews with employees of BAM (Appendix V – Interview).

The extended list of design requirements was analysed to determine the relevant design requirements. To make this distinguishment the design requirements were divided into **must-haves**, **nice-to-haves**, and **not related to process requirements**. The “not related to process” requirements are requirements that even though they are derived from the interviews are not relevant to the design of the PdM process and are therefore not included (e.g., the ability of a company to innovate). Additionally, a few requirements were not included because the requirements were not in line with the contract between BAM and Schiphol, were not relevant to the design of the PdM process or were similar to other included design requirements (Appendix IX – Design requirements).

The design requirements that were included in the design process were divided into **general requirements**, **functional requirements**, and **user requirements** (Figure 9). The categories were selected based on often applied categories in various research. Difference between the design requirements was made if they were related to the general process (general requirements), related to the useability of the process (user requirements), or if they were related to the functionality/performance of the process (functional requirements).

The “nice-to-have” design requirements are included as optional requirements. If possible optional steps were included in the PdM process that are in line with these requirements. The requirements were noted as nice-to-have requirements if they included a specific solution (e.g., algorithms for a condition indicator). This design requirement states a specific solution (algorithms) and thereby reduces the possible design decision in the PdM process.

The design requirements were validated through the use of two validation workshops. During these sessions, the requirements were discussed with various employees of BAM resulting in a few changes made to the division of the requirements over the categories. The final list of design requirements was processed into a design brief.

The design requirements in the design brief (Appendix X – Design brief) include an ID, description, criterion, priority, stakeholder, source, and result (implementation) divided over the three categories (Figure 9). The result (implementation) part of the design brief was filled in at the end of the research to determine if and thereby guarantee that all must-have design requirements were processed in the uniform PdM process. By means of the interviews, it is guaranteed that the design requirements included in the design brief are accurate. Through the use of the workshop, it is guaranteed that the design requirements are validated.

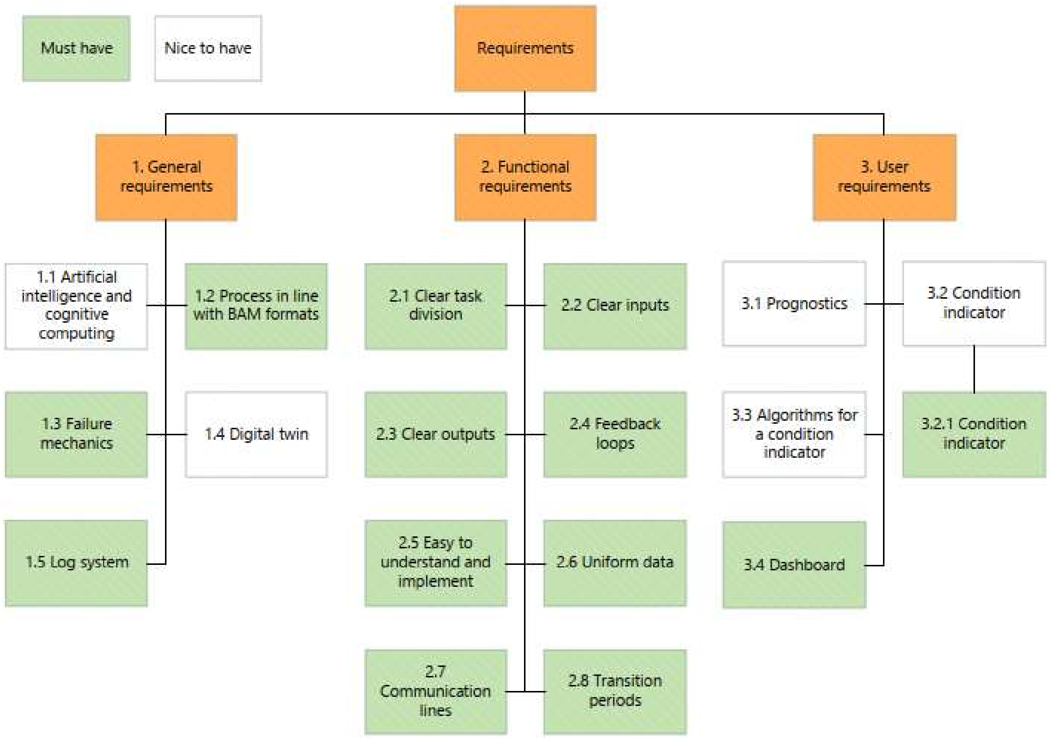

Figure 9 Categories and ID of design requirements included in the design brief

Chapter 6

PdM process

6. PdM process

With the design requirements identified in the previous chapter, the conceptual PdM process developed in Chapter 2, and the current maintenance process developed in Chapter 4, the uniform PdM process was developed to answer the third sub-question; *“How can the current maintenance process of BAM be transformed into a process suited for the implementation of PdM?”*. The PdM process was developed by transforming the current maintenance process into a PdM process based on the conceptual PdM process and several validation workshops. This is to develop a new PdM process (Figure 10) that is specifically developed for BAM. The PdM process is also added as an appendix (Appendix XI – PdM process). Between the current maintenance process and the new PdM process, several significant changes are described in this chapter.

The main changes for the new maintenance process and the corresponding changes for the organisation of BAM are seven-fold. First, the focus in the new process will lie more on identifying failure mechanisms instead of developing a FMECA-analysis.

Second, in the new process, the focus will lie on static and dynamic asset data instead of only static asset data. Corresponding to this change is the need for a new system to store the fast amount of dynamic asset data.

Third, the dynamic asset data results in the need for a new phase to pre-process the data. With static asset data, it is not needed to pre-process the data. Hence, in the current process, there is no pre-processing phase. However, with dynamic data, it is necessary to pre-process the data. Therefore, in the new process, a pre-process phase is added. Data analysts possess the necessary knowledge to implement this phase. Currently, BAM has a few data analysts employed. However, more data analysts are needed to implement PdM on a large scale.

Fourth, in the new process, it is necessary to determine when maintenance actions must be executed based on the available data instead of on pre-defined moments. Hence, a value (threshold) is needed to determine that if the data is expected to cross this value a maintenance action is executed. Furthermore, it is important to make these conclusions transparent. Hence, dashboards are needed to visualize this data.

Fifth, the development and verification of ML models is necessary if the desire is to automate the determination of maintenance actions based on the available data. In the current process, the data is manually analysed to derive maintenance actions. Development and verification of ML models require fast amount of knowledge that is not yet available at BAM and involve high investment costs. Furthermore, it is not essential for the implementation of PdM. Hence, the development and verification of ML models are included in the new process as optional phases.

Sixth, the maintenance actions derived from the process are based on different data. In the new process, the maintenance actions are derived by analysing the static and dynamic asset data. Whereas in the old process, the maintenance actions were based on static asset data and the expert knowledge of maintenance engineers.

Seventh, the PDCA-cycles included in the process are extended and the focus lies more on the reflection of the executed maintenance actions. The PDCA-cycles included in the maintenance processes are related to the executed steps. Hence, with the addition of phases and steps in the new PdM process compared to the current maintenance process, the PDCA-cycle is also extended with new steps.

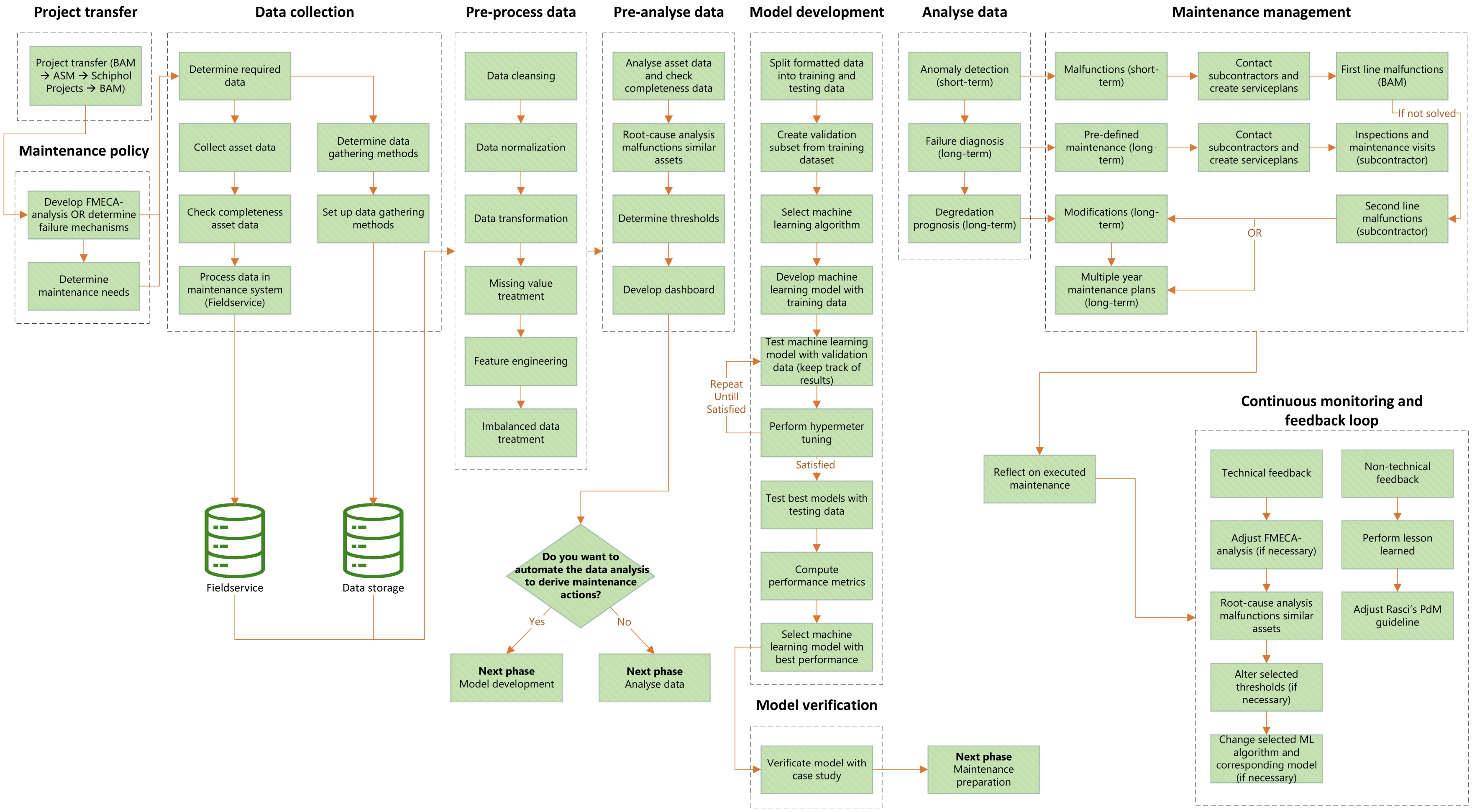

Figure 10 PdM process

6.1 Project transfer

The first phase of the PdM process remains the same as the first phase of the current maintenance process. As explained in Chapter 4 the maintenance process can start in three ways. The first is based on MYMPs. The MYMPs are proposed by the maintenance management department of BAM. The ASM department of Schiphol approves or adjusts these plans. Thereafter, the project is passed on to Schiphol Projects and then passed on again to the realisation department of BAM that starts the project. The second way is with an entire area that must be renovated. Within this project all assets are demolished and new assets are developed. The third way is with an asset needing new maintenance. For example, PdM is applied to an existing asset. Here, the project transfer is internal within the maintenance management department.

6.2 Maintenance policy

The second phase is the maintenance policy phase. Added to this phase in comparison with the current maintenance method is an adjustment made in the 'develop FMECA-analysis' activity. Here, an adjustment was made to explain that an FMECA-analysis or failure mechanisms must be developed. This for the reason that the failure mechanisms are needed to determine the needed data and to determine the maintenance needs. FMECA-analysis can be developed by following the eleven steps visualized in Figure 11 (Appendix V – Interviews code VI).

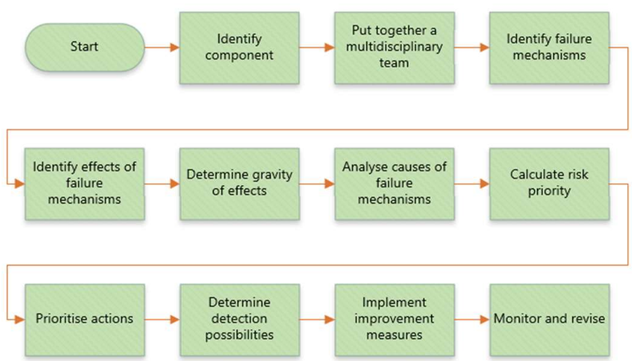

Figure 11 Stepwise process of developing FMECA-analysis (Appendix VI – Document analysis code I)

6.3 Data collection

Data collection changes quite a bit for BAM in the PdM process. Currently, BAM collects static asset data. In the new process, dynamic asset data is gathered as well. This dynamic data is needed to predict occurring failures. The data collection, checking, and processing of static asset data remains the same as the current process. The dynamic data can be gathered through new data collection methods identified in the literature review of Chapter 2. In this chapter, it was stated that there are three main types used in this research: condition data, sensor monitoring, and stressor data. The **condition data** is related to all information on the condition of the asset (e.g., inspection data). The **sensor monitoring** data is related to all data gathered from the asset including sensor data and usage data. The **stressor data** is related to all data gathered from the environment of the asset, in other words, external data.

The various data types can be gathered in several ways. Condition data can be gathered through inspections, maintenance records, and lifecycle analysis (Appendix V – Interviews Code II). According to asset managers and maintenance engineers, sensor monitoring can be gathered through temperature, oil analysis, energy (Appendix V – Interviews code I), infrared, vibrations, and acoustic (Appendix V – Interviews code II). In this research, the terms are slightly altered into infrared thermography, acoustic monitoring, current analysis, vibration analysis, and oil analysis. Stressor monitoring can be gathered with similar methods as sensor monitoring (Appendix V – Interviews code III).

In the introduction, it was explained that the FMECA-analysis, specifically the failure mechanisms and the maintenance needs determine the needed data. Additionally, the needed data is influenced by the goal of PdM. For example, if the goal is to reduce maintenance costs fewer sensors will be applied than when the goal is to increase the availability (uptime) of the asset. The failure mechanisms influence the needed data through what data is needed to predict the failure mechanisms (Appendix VI – Document analysis code I). For example, the subcomponent 'handrail' of an escalator can have wear as a failure mechanism, this mechanism can be measured with acoustic monitoring (Appendix VI – Document analysis code II).

6.4 Data storage + Digital twin

The current process of BAM includes the storage of static asset data in the maintenance system (Field Service). Various employees stated during the interviews that Field Service is too limited for storing dynamic asset data (Appendix V – Interviews). Hence, additional data storage is needed. Currently, BAM is researching data storage in a data improvement plan. Therefore, data storage was not part of the scope of this research. BAM has the ambition to develop digital twins based on collected data.

Digital twins are the virtual representation of a real-time asset. Digital twins are developed by combining data from various locations. The digital twin starts with the drawings of the building and installations. Here, the first challenge is determining the LOD (level of detail). The digital twin is used during the design, build, and maintenance process. Hence, the digital twin has distinct functions during the process with different corresponding desired LOD levels. Therefore, it is important to determine the necessary LOD level for every step in the process. For the built phase, the LOD is lower than for the maintenance phase. A possible solution is changing the LOD level when the built phase is finished. Beside the drawings data from maintenance software and data from the realisation phase (e.g., as-built drawings) are needed. The LOD level is also influenced by the desired location to store the various data. For example, the built year can be stored in the digital twin however if the asset is replaced the built year must be changed in the digital twin. The built year can also be stored in the maintenance systems where changing the data is easier (Appendix V – Interview Code V). In the digital twin, the sensors can be connected to visualize the real-time monitoring of the asset. In theory, it is possible to use the digital twin to visualize what component of the asset is malfunctioning thereby providing a clear overview of the asset (Appendix V – Interview Code V). BAM also conducts research for developing digital twins. Hence, this matter is beyond the scope of this research as well.

6.5 Pre-process data

Due to the fact that BAM only works with static asset data in the current maintenance process, the pre-processing of data was not needed. However, with the dynamic asset data included in the PdM process, the pre-processing of data is needed. Therefore, an extra phase is added to the new PdM process. In the literature review in Chapter 2 a taxonomy for the pre-processing of data by Cernuda (2019) is explained. Included in this taxonomy are (1) data cleansing, (2) data normalization, (3) data transformation, (4) missing values treatment, (5) feature engineering, and (6) imbalanced data treatment (Cernuda, 2019).

6.6 Pre-analyse data

The transformation of the current maintenance process into a new PdM process resulted in an adjustment in the name of the phase. In the current process, this phase is mentioned as the "analysis phase". However, in the new PdM process, the name is adjusted to the "pre-analyse data" phase. This decision was made because, in the new PdM process, two data analysis phases are present instead of only one phase in the current process. The first analysis phase, analyses part of the data to check if the data is complete and to determine if failure mechanisms are left out. The second analysis phase, analyses all gathered data to derive maintenance actions. Therefore, the decision was made to adjust the name of the current phase to pre-analyse data. The phase that includes the analysis of all data to determine maintenance actions is the analyse data phase. Furthermore, two steps were added to the pre-analyse data phase. Analysing the asset data, checking the completeness of the data, and performing a root-cause analysis malfunctions similar assets remain in the PdM process. Added to this phase are the development of thresholds (named KPIs in the conceptual process) and the development of a dashboard (derived from validation workshops).

Thresholds are values that if crossed initiate a certain process (Appendix V – Interview Code XI) e.g., the vibration of an escalator crosses the threshold resulting in a maintenance engineer receiving a notification. These thresholds are needed to predict when certain actions such as the replacement of components must be initiated. Based on various interviews the conclusion was drawn that asset specific threshold must be developed. However, in most cases, three thresholds will be used. The first threshold is a notification that something is off with the asset, no actions are (yet) necessary. This threshold is purely informative. The second threshold means something is off with the assets and a maintenance mechanic must take a look at the next maintenance or inspection moment. Meaning that the asset can function for another few weeks without a problem. The third threshold means the asset is not safe or not performing as desired. Hence, a maintenance mechanic must immediately perform a physical check of the asset and fix the problem (Appendix V – Interview Code XI). In most cases, this threshold is accompanied by a malfunction. These thresholds can be supported or extended with thresholds stated in the ISO (Appendix V – Interview Code II).

One of the most important design criteria is the ease of use of the PdM process. Hence, it is important to implement steps that focus on increasing the ease of use. One of these steps is the development of dashboards. The dashboard visualizes the gathered data and visualizes when values cross certain thresholds. Hence, it is important to first gather the data and derive the thresholds. This step was added based on feedback gathered through validation workshops.

6.7 Model development

Data gathered for PdM can either be analysed manually to determine maintenance actions or with the use of ML algorithms. This decision is based on numerous factors such as available time, available budget, knowledge, and the amount of automation BAM wants to include in the PdM process. Furthermore, this decision can vary per asset type. Therefore, the decision was made to include the development of a ML model as an optional phase in the PdM process.

The literature study in Chapter 2 includes a description of the development of a ML model. This process can be summarized in the following steps (Pruneski, et al., 2022)

1. Split formatted data into training and testing data.
2. Create a validation subset from the training dataset.
3. Select ML algorithm.
4. Develop ML model with training data.
5. Test the ML model with validation subset (keep track of results).
6. Perform hypermeter tuning.
7. Repeat steps 5 and 6 until satisfied with the results.
8. Test the best models of step 5 with testing data.
9. Compute performance metrics.

10. Select the ML model with the best performance.

Steps 5 and 6 are repeated multiple times to improve the performance of the developed ML models. By keeping track of the results, the best models can be selected to be evaluated with the testing data (step 8). The results of this step are the development of performance metrics. By computing these metrics in step 9 the ML model with the highest performance can be selected. The selected model forms the output of this phase. This model can be deployed in the next phase.

6.8 Model verification

BAM maintains an approximately amount of 25,000 assets on Schiphol. Therefore, it is important that the PdM process can be upscaled. However, to be allowed to upscale the process by Schiphol it is important to prove that the PdM process works. This is even more important when a ML model is used to analyse the data. This technology is relatively new on Schiphol and therefore not yet been extensively evaluated. Hence, an additional phase is made where the ML model is tested in practice using a case study. The results of the case study prove that the model works and thereby prove that the PdM process can be upscaled to include more assets of the corresponding type. Similar to the model development phase this phase is optional. This phase is only necessary if a ML model is used to determine the maintenance actions. This phase was added based on feedback gathered through validation workshops.

6.9 Analyse data

Transforming the current maintenance process into the new PdM process with the use of the conceptual PdM process resulted in an additional phase, the analyse data phase. The analyse data phase determines the necessary maintenance actions by analysing the data manually or with the use of the ML model. In the following phase (maintenance management) the identified maintenance actions from this phase are executed. The steps included in the analyse data phase to determine the maintenance are, as explained in Chapter 2, based on research executed by Serradilla, et al. (2022). In this research, four steps for the implementation of PdM are explained. These steps are (1) anomaly detection, (2) failure diagnosis, (3) degradation prognosis, and (4) mitigation (Serradilla, Zugasti, Rodriguez, & Zurutuza, 2022). Mitigation is not used in this research for the reason that mitigating the risks is performed by executing the maintenance actions in the maintenance management phase.

As mentioned, PdM can be implemented with or without a ML model. If the ML model is used, determining the maintenance actions by analysing the data can be automated. However, analysing this data can also be performed manually. This will take a lot of time and will lower the results of PdM for the reason that there is too much data to continuously analyse manually. Hence, it is advised to always use the ML model.

Analysing the data starts with detecting anomalies. Anomalies are detected by determining if the asset under normal conditions performs as intended. These anomalies can in the future result in malfunctions that can be prevented by certain maintenance actions. Based on the identified anomalies in the second step a failure diagnosis can be executed. Here, it is determined if the anomaly can result in a future failure. This failure can be prevented by executing maintenance actions. Based on this diagnosis a degradation prognosis can be made to determine the future condition. Again, this prognosis results in maintenance actions that must be executed to slow down, prevent, or fix the degradation. The three steps of the implementation of PdM result in the analysis of the gathered data and thereby deriving the maintenance actions. Here, differences can be made between short-term and long-term maintenance actions.

Anomaly detection forms the short-term data analysis of the process. The long-term data analysis of the process is formed by the failure diagnosis and degradation prognosis. The determined maintenance actions during this phase are executed in the following phase (maintenance management).

6.10 Maintenance management

The maintenance management phase forms the basis of the PdM process. In this phase, the maintenance actions determined in the previous phase (analyse data phase) are executed. Hence, the included steps in the maintenance management phase are related to executing the maintenance actions and thereby managing the maintenance.

Compared to the current maintenance process the maintenance preparation phase and the maintenance management phase are merged. The maintenance management phase includes all needed maintenance actions to perform PdM. This phase is connected to the three steps from the previous phase (analyse data).

The first steps of the maintenance management are related to the detected anomalies during the analyse data phase. If an anomaly is detected this can result in maintenance needed to prevent future malfunctions or result in direct maintenance needed to solve the malfunction. In the new process, this is included as first-line and second-line malfunctions. It is important to understand that in the new process, the perspective of malfunctions changes to executing actions to prevent malfunctions instead of only solving arisen malfunctions. The malfunctions can either be technical malfunctions or user-bonded malfunctions such as (accidentally) pressing the emergency stop (Appendix V – Interview Code XII). Part of the technical malfunctions, but especially the user-bound malfunctions can never be entirely ruled out with PdM. However, it is possible to react faster to the malfunction by gaining a better understanding of the asset through PdM (Appendix V – Interview Code VII). In some cases, modifications or MYMP are needed to prevent or solve the malfunction.

The detected anomalies are used to perform a failure diagnosis to determine if the anomaly can result in a failure mechanism. Determining this can often be done by analysing the data. In some cases, inspections must be performed to supplement the available data. The failure diagnosis is used for the degradation prognosis. By determining de degradation prognosis, it can be determined what maintenance actions must be executed to prevent or slow down the degradation of the asset. This can be performed with modification and multiple year maintenance plans (MYMP).

The short-term maintenance management of the PdM process includes the first-line and second-line malfunctions. However, contrary to the current maintenance process the first-line and second-line malfunctions maintenance actions are executed to prevent a large part of the malfunctions from arising. In some cases, these actions are used to solve spontaneously arisen malfunctions such as (accidentally) pressing the emergency stop.

The long-term maintenance management of the PdM process includes multiple year maintenance plans (MYMP), modifications, and inspections. With PdM, the maintenance of assets is still needed to keep the performance of assets high. Therefore, MYMPs will still be used. However, the MYMPs can be planned more efficiently and in the MYMPs only necessary maintenance actions are included. The modifications stem from malfunctions that cannot be solved or prevented without changing certain components of the asset. These modifications are still necessary in the PdM process. However, these modifications can be planned more efficiently by gaining a better understanding of the maintenance actions of the asset through the PdM process. For example, modifications can be planned with MYMP actions by delaying one or by bringing forward another so that it can be combined. The last part of the long-term maintenance management is the inspections.

Inspections can in theory be excluded from the maintenance management with extended and accurate PdM. However, currently, inspections are always necessary due to laws and regulations (Appendix V – Interview Code II), due to a lack of data, and due to a contract requirement included in the contract between BAM and Schiphol. Furthermore, inspections are necessary because sensors cannot measure everything (Appendix V – Interview Code XI). Therefore, in the new process inspections are still applied however this step can slowly be made to only execute the necessary inspections. In the future it may be possible to exclude inspections altogether if laws and regulations change for PdM, data collection methods improve, and the requirement included in the contract between BAM and Schiphol is amended.

6.11 Continuous feedback and monitoring

In the current process, BAM already reflects many times on the executed maintenance. However, with the PdM process new tasks were developed. These new tasks have corresponding PDCA-cycles (Plan, Do, Check, Act) that must be followed. Hence, a few steps were added to the continuous feedback and monitoring phase compared with the current maintenance process. Likewise, with the current maintenance process, the feedback loops are divided into technical and non-technical (process) feedback loops.

The technical feedback loops are related to the reflection on (1) the determined failure mechanisms or the developed FMECA-analysis, (2) root-cause analysis malfunction, (3) the selected thresholds, and (4) the selected ML algorithm and corresponding developed ML model. Separate from the technical feedback loops there is one loop that is more important than the other loops. This loop takes place before the other feedback loops and is the reflection on the developed maintenance concepts. This loop is the most important and is used to improve the maintenance management of the assets. The non-technical feedback loops are in general lessons learned of the process and reflection on the division of tasks (RASCI’s) of the PdM process.

6.12 Conclusion

The third research question reads: “*How can the current maintenance process of BAM be transformed into a process suited for the implementation of PdM?”.* The answer to this research question is that the current maintenance process can be transformed into a new PdM process by sevenfold major changes resulting in a process existing of ten phases. The phases in subsequent order are: (1) project transfer, (2) maintenance policy, (3) data collection, (4) pre-process data, (5) pre-analyse data, (6) model development, (7) model verification, (8) analyse data, (9) maintenance management, and (10) continuous monitoring and feedback loop.

The seven major changes are related to several aspects of the PdM process. Here, the most important aspects are the addition of dynamic asset data and the added analysis steps to derive maintenance actions based on this dynamic data. Furthermore, the knowledge needed for the process changes. Knowledge needed for the new process that is not yet entirely available at BAM is knowledge of the processing of dynamic asset data and knowledge of the development of the ML model to derive maintenance actions. Hence, BAM is advised to gather this knowledge through training employees or hiring extra employees with this knowledge. With this knowledge included in the organisation, the first steps can be made to implement the new process.

Chapter 7

Verification design requirements

7. Verification design requirements

In order to design a process that is in line with the wishes of BAM a design brief with design requirements was developed in Chapter 5. In this chapter, it was explained that at the end of the research, it would be verified if all design requirements were processed in the PdM process. Here, a difference was made between must-have and nice-to-have requirements. All must-have requirements were processed into the PdM process. A few nice-to-have design requirements were not processed.

7.1 General requirements

General requirements included in the design brief were (1.1) AI and cognitive computing, (1.2) process in line with BAM formats, (1.3) failure mechanisms, (1.4) digital twin, and (1.5) log system. All five requirements are processed in the PdM process (Table 5). However, requirement 1.1 is processed depending on the applied phases of the PdM process. In the PdM process, an optional phase named model development is included. By the use of this phase, the requirement is processed.

Table 5 Verification description general design requirements

ID	Requirement	Verification description
1.1	AI and cognitive computing	The PdM process developed in this research includes phases related to the development of the ML model (AI). Furthermore, certain steps such as 'develop dashboard' guarantee the accessibility of the end result for the end users. Hence, this requirement is achieved by the development of the PdM process.
1.2	Process in line with BAM formats	Based on the PdM process a guideline was developed for the implementation of the PdM process. This guideline was developed in the corresponding BAM formats.
1.3	Failure mechanisms	One of the steps included in the PdM process is 'develop FMECA-analyses'. This analysis is used to identify all failure mechanisms of the asset.
1.4	Digital Twin	The PdM process includes the development of a digital twin. The digital twin is a virtual copy of the entire physical asset and process.
1.5	Log system	Based on the PdM process a guideline is developed. The first step of this guideline has as output a log system. In the explanation, it is described that this log system is used to note under which agreements the PdM process is started.

7.2 Functional requirements

Functional requirements included in the design brief were (2.1) clear task division, (2.2) clear inputs, (2.3) clear outputs, (2.4) feedback loops, (2.5) easy to understand and implement, (2.6) uniform data, (2.7) communication lines, and (2.8) transition periods. All eight requirements were processed in the PdM process (Table 6).

Table 6 Verification description functional design requirements

ID	Requirement	Verification description
2.1	Clear task division	Based on the PdM process a guideline was developed including RASCI that divides the responsibilities of the tasks.
2.2	Clear inputs	Based on the PdM process a guideline was developed with one column visualizing inputs for all steps of the PdM process.
2.3	Clear outputs	Based on the PdM process a guideline was developed with one column visualizing outputs for all steps of the PdM process.
2.4	Feedback loops	In the PdM process a phase called 'continuous monitoring and feedback loops' is included. This phase includes multiple PDCA-cycles that are executed at the end of the PdM process.
2.5	Easy to understand and implement	Based on the PdM process a guideline was developed. This guideline makes the PdM process easier to understand. Additionally, this guideline can be used to implement the PdM process.
2.6	Uniform data	In the PdM process, three data types are used. These data types guarantee the flow of uniform data between assets.
2.7	Communication lines	Based on the PdM process a guideline was developed. Included in this guideline are RASCI's. These RASCI's explain the communication lines by mentioning which role is responsible and which roles are accountable, supporting, consulted, and informative.
2.8	Transition periods	This requirement is processed by not including transition periods. The PdM process and the corresponding guideline include clear phases that are finished after certain steps have been executed.

7.3 User requirements

User requirements included in the design brief were (3.1) prognostics, (3.2) condition indicators, (3.2.1) condition indicators, (3.3) algorithm for a condition indicator, and (3.4) dashboard. All five requirements were processed in the PdM process (Table 7).

Table 7 Verification description functional design requirements

ID	Requirement	Verification description
3.1	Prognostics	In the process and the guideline, steps are included that explain the development of a machine learning process with the goal of forecasting when failure will occur. In the PdM process within the phase analyse data to steps named failure diagnosis and degradation prognosis are included. These steps focus on forecasting when failure will happen and on calculating the remaining useful life of assets.
3.2	Condition indicators	In the PdM process a step named 'develop thresholds' is included. In this step thresholds (condition indicators) are developed based on among others decomposition, FMECA-analysis, and available data (sensors).
3.2.1	Condition indicators	The PdM process includes a step for the development of thresholds. The corresponding explanation of the step includes an explanation stating that the thresholds must be based on, among others, the ISO10816.
3.3	Algorithm for a condition indicator	The PdM process includes an explanation for the development of the algorithm. Hence, this requirement is processed in the PdM process. However, the specific implementation is dependent on the eventually developed algorithm.
3.4	Dashboard	One of the steps included in the PdM process is the development of a dashboard to visualize the data.

Chapter 8

PdM guideline

8. PdM guideline

The PdM process developed in the previous chapter was processed into a PdM guideline (Appendix XII – PdM Guideline). A guideline has been developed to provide BAM with a tool for the implementation of the PdM process. This chapter explains how the guideline was developed and validated. Furthermore, the guideline is explained in Appendix XIII – Explanation PdM guideline.

8.1 Development

The guideline was developed in a BAM-specific format (Figure 12). This format consists of (1) phase, (2) input, (3) process, (4) output, (5) RASCI, and (6) explanation. The phases included in the guideline are:

1. Project transfer.
2. Maintenance policy.
3. Data collection.
4. Pre-process data.
5. Pre-analyse data.
6. Model development.
7. Model verification.
8. Analyse data.
9. Maintenance management.
10. Continuous monitoring and feedback loops.

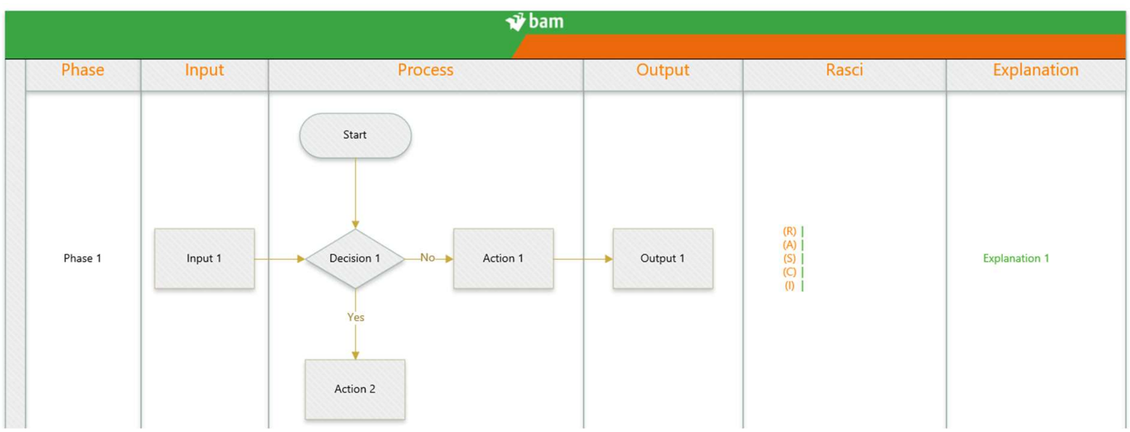

Figure 12 Format BAM

The input for the various steps in the guideline varies. The inputs are related to the phase and the specific step in the phase. For the input differentiation is made between the ML model, document, data, database, and selected approach (Figure 13). The same applies to the outputs included in the guideline. The process includes the steps of each phase. Here, a difference is made between decisions, process steps, and start/end (Figure 13).

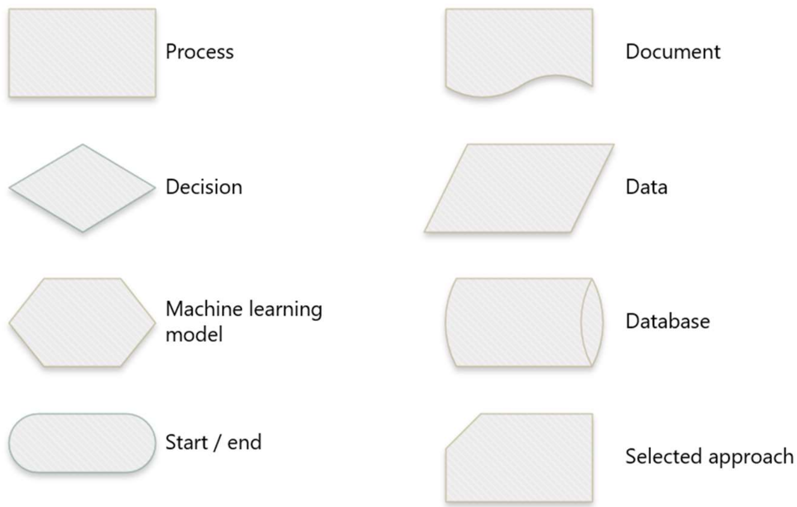

Figure 13 Shapes PdM guideline

The RASCIs (Table 8) were developed for every step in the guideline (Figure 14). As explained earlier **RASCI** stands for Responsible, Accountable, Supporting, Consulting, and Informing. The RASCI's were developed in the first workshop during the brainstorm session. Here, a difference was made between roles from BAM, from external parties (indicated with 'E') and from Schiphol (indicated with 'C').

Table 8 Roles and descriptions included in the RASCI's (Source: Appendix V – Interviews)

Role	Description
Maintenance engineer	Maintenance engineers are involved in preventive and corrective maintenance of assets on Schiphol. Furthermore, they are responsible for ensuring BAM achieves the maintenance KPIs included in the contract.
Asset manager	The asset manager is responsible for the maintenance of the assets on Schiphol. The asset manager is accountable for the maintenance engineers.
Technical manager	Technical managers are responsible for the day-to-day business of the implementation of maintenance. They are responsible for planners and technicians.
Supplier (E)	The supplier is the party that supplies the material needed for the maintenance actions. This includes the suppliers of the assets (e.g., elevator manufacturer)
Subcontractor (E)	The subcontractor is the party responsible for executing part of the maintenance actions. The subcontractor for example executes yearly inspections.
Technician	Technicians are the employees of BAM involved in solving the malfunctions that arise. Here, technicians are also involved in inspections and modifications.
Technical expert (C)	Technical experts are responsible for the maintenance policy aspects of the contract.
Planner	The planners are the employees responsible for planning the maintenance actions. This includes actions related to the development of timetables and actions related to contacting subcontractors.
Service manager (C)	The service manager focuses on customer relations.

Reliability engineer (C)	The reliability engineer is responsible for identifying and reducing the risks related to the assets.
Data analyst	Data analysts are responsible for many actions related to analysing data. For example, data analysts focus on pre-processing the data to use it to train ML algorithms.
Manager process control	The manager process control is responsible for the team process control.
Information manager	The information manager is responsible for all aspects related to managing the flow of information. This role is among others responsible for the design of the data storage.
IT architect	The IT architect is involved in IT-related activities.
Project manager	The project manager is responsible for the execution of projects. These managers are responsible for the execution of the multiple year maintenance plans.

8.2 Validation

The first workshop resulted in the development of the RASCIs included in the guideline. The second workshop resulted in the conclusion that BAM often lacks dynamic asset data needed for the implementation of PdM. Furthermore, it was concluded that BAM is not sure of the best way to collect this data. Hence, it was concluded that determining the needed data is an important first step for the implementation of PdM. Therefore, a case study (Chapter 9) was executed to provide BAM with an example of how the guideline (tool) can be used to determine the necessary data.

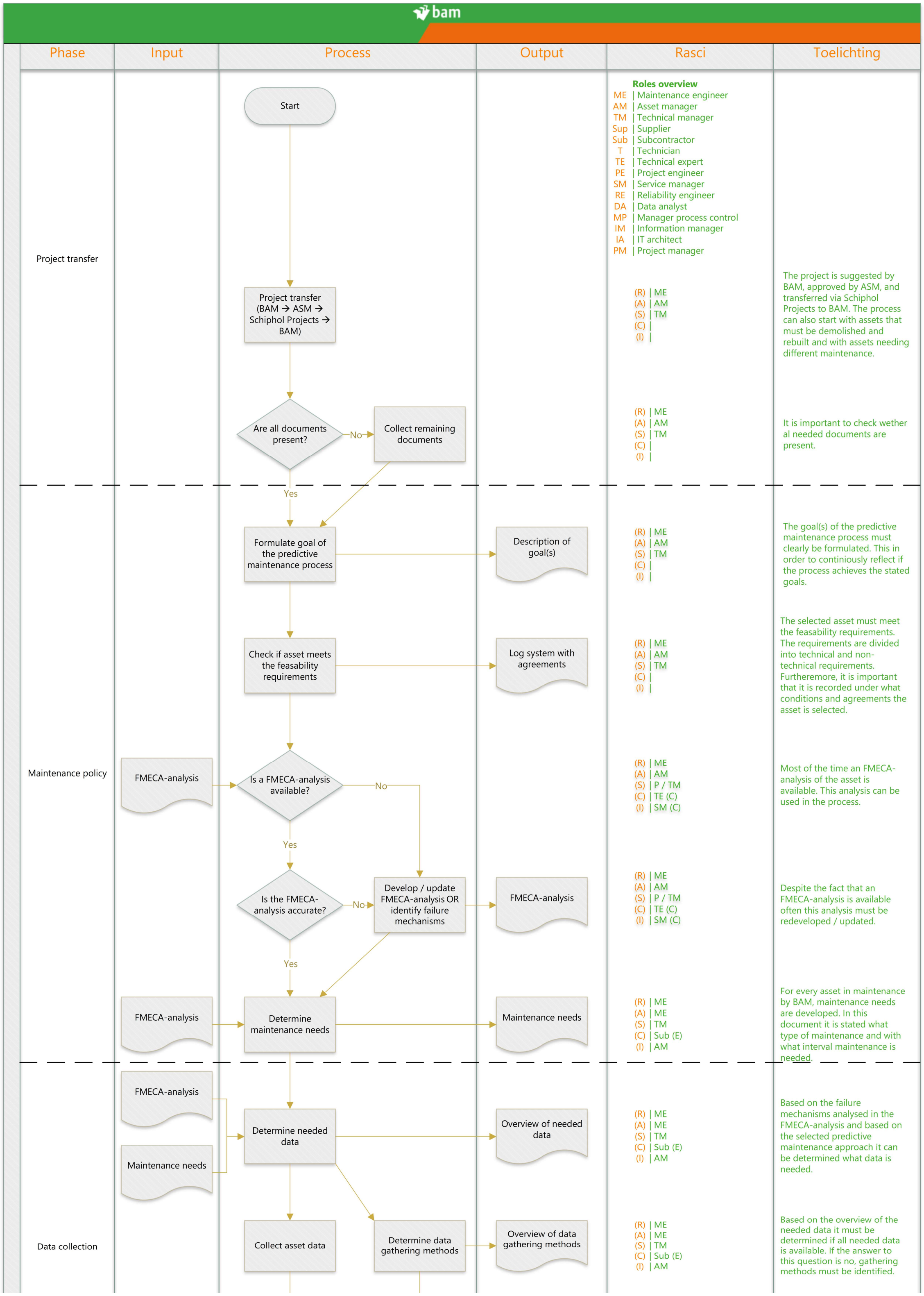

Figure 14 PdM guideline example

Chapter 9

Case study

9. Case study

In order to provide BAM with an example of how the guideline (tool) can be implemented a case study was conducted. The case study provides BAM with an example of the process to determine the needed data based on identifying failure mechanisms for an elevator. This case study was executed based on the conclusion drawn from the validation workshops that stated that the necessary dynamic asset data is not available at BAM. Additionally, it was not clear for BAM how to determine the needed dynamic asset data. Hence, this case study explains this process by execution of the first three phases of the guideline related to determining the needed data. This case study was used for the recommendation of what BAM has to do to implement PdM. The case study was conducted in cooperation with two maintenance engineers and a technical manager.

9.1 General information

The interviews (Appendix V – Interviews) concluded that transportation assets have the highest potential for the use of PdM. This conclusion is based on the fact that transportation assets perform a critical role on Schiphol and consist of various movable and electrical components. Eventually, it was decided to select elevators for the case study. This decision was based on the fact that BAM experience a challenge with maintaining the contractual agreed availability requirements (uptime) of a few of these elevators. The expectation is that implementing PdM can help guarantee the agreed uptime.

BAM maintains 111 elevators on Schiphol. From these 111 elevators, 83 elevators are above the minimal uptime norm of 98% which is mandatory on a monthly base. The remaining 28 elevators have an uptime between 69,7% and 97,8% on a monthly basis. The elevator with the lowest uptime is elevator 53. It is expected that implementing PdM for elevator 53 has the most potential to show the benefits of PdM. Hence, elevator 53 is selected for the case study.

Elevator 53 was built in 1998, making it one of the older elevators on Schiphol. Currently, BAM performs maintenance five times per year. Not included in this are the modifications, projects related to the multiple year maintenance plan, and the malfunctions that arise. Included in the five times maintenance are four quarter-year maintenance visits and one yearly maintenance visit. The costs related to these maintenance visits vary based on anomalies that are discovered during the visits. The average costs of these visits are 3700 euros. Modifications and multiple year maintenance plans vary every year and are not executed every year. Hence, it is not possible to provide cost estimations for these two flows. The malfunction varies every year as well. Therefore, it is not possible to provide a cost estimation.

The registered malfunctions of elevator 53 since 2019 can be seen in Figure 15. From this figure, it can be concluded that not all malfunctions can be prevented by implementing PdM. However, part of the malfunctions can be prevented to achieve the goal of increased uptime. The user-bound malfunctions (e.g., molestation) cannot be solved. This also applies for malfunctions outside of the influence of BAM. The main malfunctions with the highest potential that can be solved with PdM are wear and adjustment-/ assembly errors.

It can be concluded that elevator 53 has the highest potential to implement PdM. Hence, this elevator is used for the case study. The goal of the implementation of PdM for elevator 53 is to increase the uptime from 69,7% to at least 98% on a monthly base. Here, higher maintenance costs are acceptable if the goal is reached. It is not possible to execute a lot more maintenance to achieve this goal because part of the maintenance activities results in the elevator not being available. Hence, more maintenance results in a lower uptime.

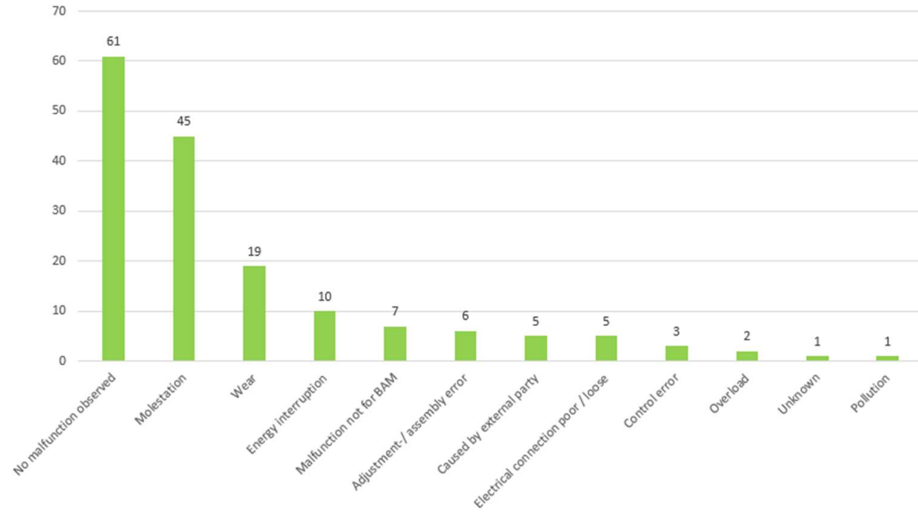

Figure 15 Malfunctions elevator 53 since 2019

9.2 Implementation guideline

The first three phases of the guideline were implemented for elevator 53. The focus was only on the first three phases for the reason that based on the validation workshops the conclusion was drawn that dynamic asset data is not available at BAM and BAM is unaware of how the process to determine this data is executed. Hence, by implementing the first three phases of the guideline related to determining the needed data, this case study helps BAM with the implementation of PdM.

The executed steps of the guideline are mentioned and explained in Table 9. Below the steps are further explained and the results of the steps are shown.

Table 9 Guideline steps and explanation case study

ID	Step	Implementation
1	Are all documents present?	Yes, however, these documents are not from the original asset. Over the years new documents were developed during inspections, maintenance, and modifications.
2	Formulate the goal of the PdM process	The goal of the implementation of PdM for elevator 53 is to increase the uptime of elevator 53 to at least 98% on a monthly base. Currently, the uptime is 69,7%. This is too low and can result in problems for BAM in the future.
3	Check if the asset meets feasibility requirements	Elevator 53 meets all feasibility requirements. Therefore, it can be concluded that PdM can be used to maintain elevator 53.
4 5	Is a FMECA-analysis available? Is the FMECA-analysis accurate?	Yes, the original FMECA-analysis is available. However, two problems are encountered with the analysis. Firstly, the FMECA-analysis is too specific for use in the PdM process. Secondly, the FMECA-analysis is outdated and not in line with the knowledge of the assets available at BAM. Hence, even though an FMECA-analysis is available, it cannot be used in the PdM process. Therefore, failure mechanisms are identified based on the knowledge at BAM and based on the NEN2767.
6	Determine maintenance needs	Five times per year, four quarter-year maintenance visits and one yearly maintenance visit.

7	Determined needed data	The needed data is determined by connecting failure mechanisms with data types. It was concluded that condition data and sensor monitoring data are applicable for the PdM process for elevator 53.
8	Collect asset data	Asset data is already registered in Field Service and thereby collected.
9	Check completeness asset data	Asset data is not complete. However, the data needed for PdM is complete.
10	Field Service	Not all data is included in Field Service. However, the data needed for PdM is included in Field Service.
11	Determine data gathering methods	Based on failure mechanisms data gathering methods were identified. It was concluded that a difference is made between general and specific sensors.

Are all documents present (1)

Elevator 53 is an old elevator built in 1998. Most of the documents related to this elevator were not present. Over the years various documents containing various data were developed through inspections. This data was used to determine failure mechanisms.

Goal of PdM process (2)

The main goal of the PdM process is to increase the uptime of elevator 53. Even if maintenance costs increase, this goal must be achieved.

Feasibility requirements (3)

In the guideline, it was explained that the asset must have a certain type of failure mechanism, must have various measurable movable and/or electrical components, and the failure mechanisms must be possible to predict by gathering data. Furthermore, it was explained that the asset must either be a critical asset, that maintenance actions can be reduced by the implementation of PdM, or that maintenance costs can be reduced by the implementation of PdM. If the asset meets the mentioned feasibility requirements the asset is feasible for maintenance with PdM. Table 10 shows the answer to the six mentioned aspects. From this, it was concluded that the asset meets the feasibility requirements. Hence, it was concluded that PdM is feasible for elevator 53. It can also be concluded that PdM is feasible for elevators in general.

Table 10 Feasibility check elevator 53

ID	Question	Answer
1	Type of failure mechanisms	A (mostly)
2	Asset has various measurable movable and/or electrical components	Yes
3	Failure mechanism can be predicted by gathering data	Yes
4	Asset is critical for the core function of Schiphol	Yes
5	Maintenance actions can be reduced by the implementation of PdM	Yes
6	Maintenance costs can be reduced by the implementation of PdM	No

FMECA-analysis or failure mechanisms (4 & 5)

The decision was made, based on the limited time reserved for the case study, to identify failure mechanisms instead of developing a FMECA-analysis. It is however advised to always develop a FMECA-analysis. The failure mechanisms were identified and assigned to specific components of the elevator. Therefore, a decomposition was made. The decomposition was made by using the decomposition included in the old FMECA-analysis of elevator 53. This analysis could not be used for the failure mechanisms because it was outdated. However, the decomposition was still accurate and was therefore used. The decomposition (Figure 16) was validated through conversations with two maintenance engineers and a technical manager. In order to assign failure mechanisms to the components of elevator 53 a long list of failure mechanisms was developed. This list was developed based on the NEN2767 and the old FMECA-analysis. Thereafter, the failure mechanisms were in consultation with a maintenance engineer assigned to specific components of the elevator. The failure mechanisms clustered per component are added in Appendix XIV – Failure mechanisms overview. This appendix was validated through two separate conversations with a technical manager and a maintenance engineer. By means of the validation, it can be concluded that all failure mechanisms are identified and assigned to the corresponding components.

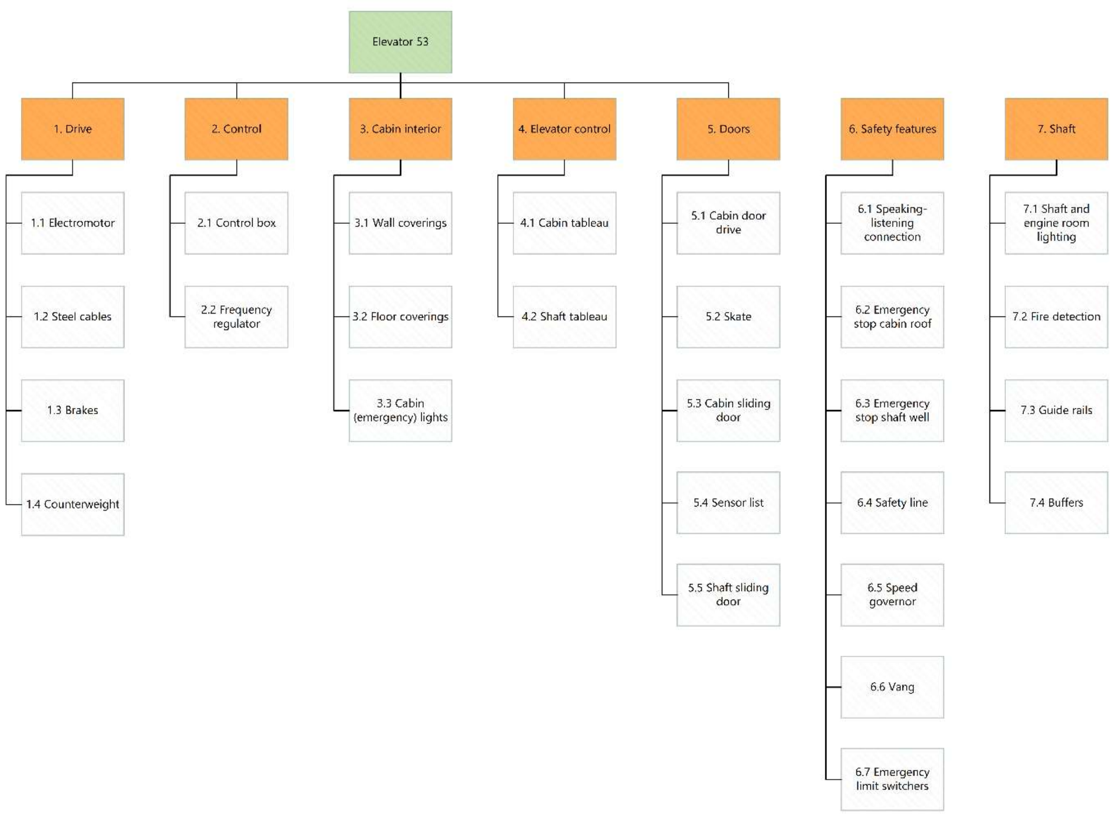

Figure 16 Decomposition elevator 53

Maintenance needs (6)

At the start of the contract (April 1, 2019) maintenance needs for all assets were developed. The maintenance needs for elevator 53 were changed over the years due to a decrease in condition. Currently, the maintenance needs are five times a year. This maintenance includes four quarter-year maintenance visits and one yearly maintenance visit. However, with PdM, it is possible to reduce the amount of maintenance. Hence, the maintenance needs must be adjusted at the end of the process based on the amount of needed maintenance determined by the PdM process.

Determine needed data (7)

The needed data is divided into static and dynamic asset data. The static asset data is partly present and collected. The dynamic asset data needed for PdM is not available for elevator 53. The dynamic asset data can be collected through the explanation included in step eleven; determine data gathering methods.

Collect asset data (8)

All available static asset data was collected and processed in Field Service. Visualizing the static asset data in this research was not possible because the data contained sensitive information. The static asset data is only collected in the first three phases of the case study and not yet used. The use of the data takes place further in the process. Therefore, it can be concluded that based on the focus of the case study visualizing the static asset data in this research is not important.

Check completeness of asset data (9)

During the check, it was concluded that part of the static asset data of elevator 53 was missing. This conclusion is based on empty fields in Field Service. However, from the analysis, it was concluded that almost all the missing data is not relevant for the implementation of PdM. Hence, with the focus on PdM, most of the necessary static asset data is complete. The only missing data is related to the operating hours and movements of the elevator. This data can however be gathered through technology already included in the asset. This data is present at Schiphol and can be requested by BAM.

Field Service (10)

The available data has already been processed into Field Service.

Determine data gathering methods (11)

Based on the failure mechanisms data gathering methods were identified. Included in the PdM process are three types of data: condition data, sensor monitoring, and stressor monitoring. In this case study condition data and sensor monitoring data were included. It was concluded that elevator 53 is not influenced by external factors. Hence, stressor monitoring data was not included.

The condition data used in the case study was the data from previous inspections. This data is available and therefore this data does not need to be gathered. This data is not visualized in this research for the reason that similar to static asset data, this data contains sensitive information. The workshops concluded that sensor monitoring data is not available. Hence, this data has to be gathered by determining the necessary data collection methods. The collection methods can be identified by using the failure mechanisms to determine the needed data to predict when the failure mechanisms will occur.

The failure mechanisms assigned to the components of elevator 53 included in Appendix XIV – Failure mechanisms overview are used to determine what data collection methods are needed. Determining the data collection methods is performed by determining for every failure mechanism per component how this can be measured. Here, the data can be gathered through infrared thermography, current analysis, acoustic monitoring, vibration analysis, oil analysis, or cameras. Determining the gathering methods is performed in cooperation with a maintenance engineer. Afterwards, this list was validated with a technical manager. The overview of this list is added in Appendix XV – Data gathering overview. This list however includes in some cases the same sensor multiple times for one component while in practice this sensor will only be used once. Therefore, the list is transformed into an overview where per component is visualized what sensor can be applied to collect data to predict failure mechanisms. This overview is visualized in Figure 17. Here, a difference was made between a general sensor and a sensor specific for a component. This list was once again validated through conversations with a maintenance engineer and a technical manager.

Element function	Component	Data gathering methods							
		infrared thermography	Acoustic monitoring	Current analysis	Vibration analysis	Oil analysis	Camera elevator	Camera floors	Not possible
Drive	Electromotor			x	x				
	Steel cables								x
	Brakes		x						
	Counterweight				x				
Control	Control box	x		x					
	Frequency regulator	x		x					
Cabin interior	Wall coverings						x		
	Floor coverings						x		
	Cabin (emergency) lights			x			x		
Elevator control	Cabin tableau			x			x		
	Shaft tableau			x				x	
Doors	Cabine door drive		x		x				
	Skate		x						
	Cabin sliding door		x		x		x		
	Sensor list			x					
	Shaft sliding door		x		x			x	
Safety features	Speaking-listing connection			x					
	Emergency stop cabin roof			x					
	Emergency stop shaft well			x					
	Safety line								x
	Speed governor				x				
	Vang								x
	Emergency limit switchers								x
Shaft	Shaft and engine room lighting			x					
	Fire detection			x					
	Guide rails				x				
	Buffers								x

Green	Possible, advised
Yellow	Possible, not advised (few malfunctions and low impact)
Red	Not advised, zero to almost zero malfunctions

Figure 17 Data gathering methods per component of elevator 53

The infrared thermography, camera elevator, and camera floors are general sensors. The infrared thermography is one sensor applied in the engine room of the elevator. The camera elevator is one camera applied in the elevator. The camera floors are one camera per floor where the elevator stops. The remaining data gathering methods are sensors applied specifically to the component. Furthermore, it can be seen that three distinct colours are used for the sensors. Green visualizes the advice to apply this data gathering method. Yellow visualizes that applying this data-gathering method is possible, but not advised based on the few malfunctions that arise and the minimal impact of these malfunctions. For these data gathering methods, it is cost-benefit not advised to apply the sensors. Red also visualizes that it is not advised to apply the data gathering method. However, in this instance, red means zero to almost zero malfunctions. Based on the above-explained analysis and based on the analyses of Figure 17 the following data gathering methods suggested in Table 11 are advised.

Table 11 Data gathering methods

Sensor	General/specific	Component/location
Infrared thermography	General	• Engine room
Camera	General	• Elevator • Floors
Current analysis	Specific	• Electromotor • Frequency controller • Cabin tableau • Shaft tableau

		• Sensor list • Speaking-listening connection • Emergency stop cabin roof • Emergency stop lift well • Speed governor • Shaft and engine room lighting • Fire detection
Acoustic monitoring	Specific	• Brakes • Cabin drive • Skate
Vibration analysis	Specific	• Electromotor • Cabin drive • Speed limiter

It was concluded that the above-explained data is not yet available. Therefore, this data has to be gathered by means of the above-explained data-gathering methods. This case study can be used by BAM to gather the needed data. Thereafter, BAM can decide to implement the remaining part of the guideline for elevator 53.

9.3 Conclusion

The goal of the case study was to provide BAM with an example of how the guideline (tool) can be used to determine the needed dynamic asset data based on identified failure mechanisms. Therefore, the first three phases related to determining the needed asset data were implemented for elevator 53 in the case study. From the case study, it was concluded that BAM must implement the sensors mentioned in Table 11 to gather the necessary dynamic asset data. Additionally, BAM is advised to use this case study to implement the remaining part of the guideline on elevator 53. Here, the main challenges BAM faces are the gap in knowledge to automate the data analysis process and the knowledge gap to derive maintenance actions from the PdM process. These gaps can be solved by training the employees or by hiring extra employees who possess this knowledge.

A point of attention of this case study is that it must be determined if the identified data gathering methods gather the needed information. This can be assessed by applying the sensors on elevator 53 or by applying the sensors on a mock-up. If all needed data is gathered it is important to determine how maintenance actions are derived from this data. Here, a continuous PDCA-cycle must be followed to check if the maintenance actions derived from the data are accurate and reliable.

Chapters 10 & 11

Conclusion & Discussion

10. Conclusion

This research aimed to develop a uniform PdM process for BAM in order to answer the Research Question: *"How can PdM be implemented for assets such as walkways, escalators, and elevators based on a uniform PdM process to decrease downtime, increase asset reliability, and decrease maintenance costs?"*. Therefore, a qualitative study was conducted to develop a PdM process, identify the current maintenance process of BAM, and integrate these two processes into a new PdM process.

The developed conceptual PdM process, based on an extensive literature review, consists of seven phases. In subsequent order the phases are (1) determine failure mechanisms, (2) data collection, (3) pre-process data, (4) pre-analyse data, (5) model development, (6) analyse data, and (7) continuous monitoring and feedback loop.

Certain assets, especially critical assets with various moving components, are very suited for the implementation of PdM. Factors influencing the feasibility of PdM for assets are the technical and cost-benefit feasibility. The technical feasibility is determined by the amount of movable and/or electrical components, if the assets have failure mechanisms type A, B, C, D, E, or F as identified by the RCM cycles, and if the assets have failure mechanisms that can be predictive by collecting and analysing static and dynamic asset data. The cost-benefit feasibility is determined by a consideration of performance, risks, and costs. Most of the interviewees mentioned that transportation assets (e.g., escalators, elevators, and moving walkways) have the highest potential for the implementation of PdM. Furthermore, the interviews supported the conclusion that with a few adjustments the organisation of BAM can be made suitable for PdM. The main adjustments are related to the supply and processing of data resulting in the need for more knowledge, new employees, and the training of current employees.

The current maintenance process, consisting of seven phases, focuses on pre-defined maintenance actions based on static asset data as was concluded from the interviews and other conversations with maintenance engineers. The phases in subsequent order are (1) project transfer, (2) maintenance policy, (3) data collection, (4) data analysis, (5) maintenance preparation, (6) maintenance management, and (7) continuous monitoring and feedback loop.

A thorough list of requirements, identified through the interviews, was processed into a design brief to support the design process of the PdM process. Here, it was concluded that the eighteen important design requirements are related to general requirements, user requirements, and functional requirements.

The new PdM process, consisting of ten phases, focuses on predicting maintenance actions based on static and dynamic asset data. The phases in subsequent order are (1) project transfer, (2) maintenance policy, (3) data collection, (4) pre-process data, (5) pre-analyse data, (6) model development, (7) model verification, (8) analyse data, (9) maintenance management, and (10) continuous monitoring and feedback loop. The main changes related to the new PdM process are related to the addition of dynamic asset data resulting in the need for a new storage system, new phases related to the pre-processing and analyses of dynamic asset data, and the switch to predicting maintenance actions instead of pre-defined maintenance moment. Furthermore, the fast amount of data results in the desire for additional phases related to the development and verification of ML models to automate the data analysis. The identified changes result in various changes for the organization of BAM. With the increased focus on data within the PdM process, the need for data analysts increases. Furthermore, with the increase in complexity of the maintenance process, the need for a uniform guideline arises.

A guideline was developed based on the PdM process to increase the ease of implementation of the PdM process. Through two validation workshops, the PdM process and corresponding guideline were validated. Based on these workshops, it was concluded that BAM does not have the necessary dynamic asset data for the implementation of PdM. Therefore, the decision was made to execute a case study to provide BAM with an example on how to determine the data collection methods to gather the necessary dynamic asset data.

This research has shown that a uniform PdM process has the focus on static and dynamic asset data for the prediction of maintenance actions. Included in the process are ten phases related to the collection, pre-processing, and analyses of the data to predict the maintenance actions. However, to implement PdM, BAM must undergo certain adjustments such as hiring new employees, training the current employees, and collecting more data.

11. Discussion

The outcomes of this research have provided BAM insights in the implementation of PdM. However, the results of this study have some limitations that can be solved with future research. Within this chapter, a reflection on the research process is provided including limitations and potential consequences of the PdM process. Furthermore, recommendations are given for future research and further steps BAM is advised to take for the implementation of PdM. The provided recommendations are divided into company (BAM) specific recommendations and recommendations applicable to the construction industry in general.

11.1 Company

This research resulted in four recommendations specific to BAM. These recommendations are related to adjustments for BAM and follow-up steps for the implementation of PdM.

The first recommendation is related to the standardization of the maintenance process. In the new maintenance process, it is important to realize that not all assets have the same solution. The maintenance process can no longer be seen as a standardized solution for all assets of the same type. The maintenance actions that are predicted for elevator X are not always the most effective maintenance actions for elevator Y. In the new process, a switch must be made to situation-based maintenance by means of analysing the data for the specific asset. Here, the developed uniform PdM process and guideline can be used to implement this. Therefore, BAM is advised to use the uniform PdM process and guideline to implement PdM for various assets.

The second recommendation is related to the assets that are suitable for the implementation of PdM. This research provided a long list of assets that are suited for the implementation of PdM. Furthermore, it was concluded that the transport assets have the highest potential for PdM. Therefore, BAM is advised to first implement PdM for transport assets followed by the implementation of PdM for the remaining asset types provided in the list. For the implementation of PdM for transport assets, BAM is advised to first implement PdM for elevators by further conducting the case study. The case study provides the data collection methods necessary for collecting the needed data for the implementation of PdM.

The third recommendation is related to the collection and processing of data needed for the implementation of PdM. In the new process, the importance of data has increased. Here, static and dynamic data must be gathered and processed. Additionally, preference must be given to automate the gathering and analysing of the data to predict maintenance actions to increase the benefits of PdM. Therefore, BAM is advised to implement all phases included in the uniform PdM process and guideline.

The fourth recommendation is related to preparing the organisation for the implementation of PdM. Often static data is the only type of data that is used for determining maintenance actions. In the new PdM process, static and dynamic data is used resulting in more data gathering and processing. The knowledge needed for this is not entirely present within the organisation. Additionally, the organisation does not always have the necessary capacity to implement PdM. Therefore, BAM is advised to first gather the needed knowledge by training employees and/or by hiring new employees with this knowledge. Secondly, BAM is advised to increase its capacity by hiring new employees. Last of all, BAM is advised to include all hierarchical levels in the transformation to PdM. This can be done by including various employees and by implementing a strongly supported vision of PdM.

The last recommendation is related to implementing PdM for BAM in general. This research provided a uniform PdM process for BAM. However, this process can also be used for the maintenance of assets on different locations. Therefore, BAM is advised to conduct future research to determine if this uniform process can directly be used to implement PdM on other locations. Currently, PdM is not used within the organisation of BAM. By using the tools provided in this research it is possible to help implement PdM on various locations.

A limitation of the research is the fact that no practical examples from other companies are included in this research. Future research can be conducted to determine if there are certain solutions on the market that can increase the ease of implementation of PdM.

Summarized, it can be stated that BAM needs to continue this research to implement PdM. The steps to continue this research consist of understanding the new uniform PdM process, researching additional suitable assets for the implementation of PdM, further conducting the case study, and preparing the organisation for the implementation of PdM by gathering the necessary knowledge. Hence, this research provides BAM with the necessary steps to implement PdM on Schiphol and on other locations that include similar assets.

11.2 Construction industry

This research moves towards the implementation of PdM and thereby predicts when assets need maintenance instead of executing pre-determined maintenance actions that might be unnecessary. This research provides a uniform process that cannot only be used by BAM but can also be used in the entire construction industry to implement PdM for various assets.

A future development from this research is, in how to address the maintenance of assets. In general, the maintenance is executed on pre-defined moments in the construction industry. In the future, the maintenance can be executed at predicted moments in time. However, to realize this implementation, the practical aspects of PdM must be understood. This research can help in understanding this. Still, there are a few unsolved questions that were not answered in this research.

The outstanding questions are questions such as “Can all necessary data for predicting failure mechanisms be gathered?”, “How can the data be stored?”, and “How effective are the ML models in predicting maintenance actions?”. These questions can be answered with future research. Here, the first question related to the necessary data is the most important. The data is the largest contributor to determining the success of the PdM process.

There are a few limitations to the conducted research that result in possible future research. Firstly, the literature review included in this research is limited due to the brief period the research was conducted. Hence, it is advised to conduct an even more extensive literature review to gather more information about the PdM process. Secondly, the focus of the research was on transport assets. However, it is possible that for the other disciplines, the PdM process slightly changes. Therefore, future research must be conducted to determine if the PdM process needs adjustments for the remaining disciplines.

This research provided a new PdM process that was developed by following a pre-defined design process. The developed PdM process has the most potential if the process is made more specific for the company that is implementing PdM. Therefore, it is important to understand and follow the design process to adjust the PdM process. The design process starts with identifying the problems, followed by determining design requirements, developing a new process and afterwards validation of this process. The focus of this research was to transform the current process into a new PdM process. Therefore, it was also important to identify the current process. By means of following the design cycle, the chance of developing a new successful process that is supported throughout the organisation can be increased. Here, all “must-have” design requirements must be processed into the new process.

Therefore, it can be concluded that there are two major design advice; the design cycle must be followed and all important design requirements must be processed into the process.

The literature provided a clear process for the implementation of PdM. However, in this process, several aspects were not included that are important for the successful implementation of PdM within the construction industry. The most important aspects that are identified from this research that were not included in the literature are threefold.

The first aspect is the connection between determining the needed maintenance and execution of the determined maintenance. In the literature, a three-step process is available for determining maintenance actions based on PdM. However, these steps do not include how the determined maintenance can be executed. This research connects the three-stepwise process with the maintenance management of BAM to provide clear insights into this aspect.

The second aspect is related to implementing PdM for existing assets. The literature focuses on implementing PdM on new assets and therefore having the ability to collect all data that is needed to implement PdM fully. In this research, steps are included in the process that explains how to implement PdM for existing assets. Additionally, the case study included in this research provides an example on how to collect the necessary data for the implementation of PdM for existing assets.

The last aspect is related to the suitability of PdM. In the literature, it is suggested that PdM can always be used to improve the maintenance of assets. However, in this research, it is explained that even though technical it is possible to implement PdM, this is not always advised when considering the possible financial gain or yielded benefits. This consideration is not mentioned in the literature.

Summarized, it can be stated that even though this research moves to the implementation of PdM, the results can be improved with future research. The results can be improved by conducting research for the unsolved questions, by extending the literature review, and by adjusting the process for all disciplines. This research provides three adjusted insights compared to the literature. These insights are related to the connection between determining the needed maintenance and execution of the determined maintenance, the implementation of PdM for existing assets, and determining the suitability of PdM for assets.

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Appendices