DECISION SUPPORT SYSTEM FOR CONDITION MONITORING

ABDERRAHIM MOUATAMIR

Decision Support System for Condition Monitoring Technologies

---

ABDERRAHIM MOUATAMIR

Graduation Committee

Chairman and PDEng-program director

Prof. dr. ir. D. Schipper

University of Twente

Supervisor

Prof. dr. ir. T. Tinga

University of Twente

Co-supervisor

Dr. ir. R. Loendersloot

University of Twente

Members

Dr. ir. R. Bosman

University of Twente

H. Roeterink (Msc.)

DNV-GL Groningen

Decision Support System for Condition Monitoring Technologies

Mouatamir, Abderrahim

PDEng thesis, University of Twente, Enschede, The Netherlands

March 2018

ISBN: 978-90-365-4519-8

DOI: 10.3990/1.9789036545198

<https://doi.org/10.3990/1.9789036545198>

Printed by Gildeprint, Enschede, The Netherlands

Cover design by University of Twente

Copyright ©2018 A. Mouatamir, Enschede, The Netherlands

All rights reserved.

DECISION SUPPORT SYSTEM FOR CONDITION MONITORING
TECHNOLOGIES

PDEng Thesis

to obtain the degree of
Professional Doctorate in Engineering (PDEng) at the University of Twente,
on the authority of the rector magnificus,
prof. dr. T.T.M. Palstra,
on account of the decision of the graduation committee,
to be defended
on Wednesday the 28th of March 2018 at 13:00

by

Abderrahim Mouatamir
born on 27 December 1989
in Nieuwegein, The Netherlands

This PDEng thesis is approved by:

Thesis supervisor: Prof. dr. ir. T. Tinga

Thesis co-supervisor: Dr. ir. R. Loendersloot

Summary

The technological feasibility of a condition-based maintenance (CBM) policy is intrinsically related to the suitable selection of condition monitoring (CM) technologies such as vibration- and oil analysis or other non-destructive testing (NDT) techniques such as radiographic- and magnetic particle testing. However, in practice the selection can be quite complex due to the tremendous number of variables that need to be taken into account. These variables can be classified into three categories: (1) variables that are inherently related to the features of the system to be monitored (e.g. material composition, geometry and motion); (2) variables that are related to the supposedly selected CM technology(-ies) (e.g. physical limitations and diagnostic capabilities); and (3) variables that are related to the failure mechanism under which the system predominantly fails (e.g. corrosion, wear and fatigue). Finding the optimum combination of these variables, with the aim of selecting the most suitable CM technology(-ies), is the objective of the decision support system (DSS) presented in this thesis.

To this end, an expert system (ES) was developed to assimilate the tremendous amounts of variables while taking into consideration a set of predefined requirements. The knowledge domain behind the ES-based DSS was structured in such a way that all patterns, i.e. combinations of selection variables, leading to an appropriate CM technology could be developed, tested and validated.

To develop these patterns, rule-based reasoning (RBR) was used. Within this context, RBR is a particular type of reasoning where a set of designated “if-then” statements are assigned to a particular CM or NDT technique. The patterns that match the decision-makers’ provided facts result in a successful selection outcome. Furthermore, testing and validating the corresponding outcomes required actual case-studies (from literature) where technologically feasible CM techniques have been successfully employed. A case-study contributes to validating the DSS when its selection outcome corresponds to the actual CM strategy in question.

The design project is documented in the present thesis. The design deliverable was designed according to the standards of design methodology. It iterated the design cycle four times. The end results during both the design- and validation phases are presented according to the outcomes of the last iteration.

Acknowledgements

During my Master program in Mechatronics, I was introduced for the first time to the notion of maintenance in general, and to condition-based maintenance (CBM) in particular. I was continually exposed to various concepts ranging from technical complications to the economic challenges CBM faces. All in all, I gained a broad theoretical knowledge that strengthened my understanding and laid the foundation of the end-approaching Professional Doctorate in Engineering (PDEng) I am involved in. In fact, my PDEng-traineeship in Maintenance Engineering has offered me a pragmatic attitude towards CBM and helped its implementation, even partially, in a real-life context.

Many people in the industry were sceptical about the feasibility of designing a selection method that brings all condition monitoring (CM) technologies together. Although proven realizable (knowing of course that this work is still subject to critique), it would not have been possible without the assistance I received from my supervisors, namely, Tiedo Tinga and Richard Loendersloot. Tiedo and Richard are far more familiar with maintenance than I am. Our discussions used to be fruitful thanks to the constructive and critical feedback. Thank you both for the meticulous adherence to proper supervision and guidance.

For sure, this work would not have been tested nor validated if it was not for Axel Homborg and Huub Roeterink. Axel's expertise in corrosion and Huub's professionalism in providing the necessary case-studies for this work both facilitated the project's validation phase. Thank you both for making this work possible.

And then there was Debbie. Debbie Zimmerman van Woesik is the most kind and the most helpful secretary in the universe. I cannot imagine how much time I would have spent on administrative issues without Debbie's help. Thank you for helping me on my first day at the university, thank you for helping me on my last day, and everyday in between.

Finally, my colleagues who became, as time went on, one of my closest friends: Dimitris Karampelas from Greece and Mohammad Kojourimanesh from Iran. "@ Dimitris : You are the best Greek I have ever known (probably because you are the only Greek I know :-p). I always admired your extrovert-and sociable character, your perseverance and determination, and above all your positiveness". "@ Mohammad : Thank you for providing me the opportunity to document one of the case-studies, it was an added value to this work. You are a kind and warm person, ambitious and enthusiastic. It is really something that I admire about you." I would also like to thank all members of the dynamics-based maintenance group, Tung Tran and Damian Rommel in particular.

Contents

Summary	v
Acknowledgements	vii
List of Figures	xi
List of Tables	xiii
List of Abbreviations	xv
1 Introduction	1
1.1 Background & Motivation	1
1.2 Objectives	1
1.2.1 Description of the design challenge	1
1.2.2 Design Challenge	2
1.2.3 Approach	3
1.3 The Design Project Outline	5
2 Requirements Engineering	7
2.1 Introduction	7
2.2 Stakeholder Analysis	8
2.2.1 Main stakeholders	8
2.2.2 The Problem Domain	9
2.2.3 The Solution Domain	13
2.3 Writing & Reviewing Requirements	14
2.3.1 Transformation of needs into requirements	14
2.3.2 List of requirements	15
3 Design Methodology	19
3.1 Systems thinking	19
3.2 Design Methodology	23
3.2.1 Introduction	23
3.2.2 The Design Cycle	24
3.2.3 The Engineering Cycle	28
4 Designing the Decision Support System	31
4.1 Introduction	31
4.2 Corrosion Monitoring	33
4.2.1 <i>Category [T]</i> : Corrosion Monitoring Techniques	33
4.2.2 <i>Category [A]</i> : Attributes related to the system of interest	35

4.2.3	<i>Category [B]</i> : Attributes related to the supposedly selected corrosion monitoring strategy	38
4.2.4	<i>Category [C]</i> : Attributes related to the underlying corrosion mechanism	43
4.3	Wear Monitoring	45
4.3.1	<i>Category [T]</i> : Wear Monitoring Techniques	45
4.3.2	<i>Category [A]</i> : Attributes related to the system of interest	48
4.4	Assimilation phase	50
4.5	ES-based DSS Integration in other CBM Guidelines	55
5	Validation by Case-studies	57
5.1	Validation based on literature case-studies	58
5.1.1	Corrosion monitoring using the field signature method inspection tool	58
5.1.2	Acoustic Emission for Corrosion Detection	60
5.1.3	Corrosion Monitoring in Marine Environment in Croatia	61
5.2	Validation based on a documented case-study	63
5.3	Observation based on a conducted case-study	64
6	The Design Project Deliverable	67
6.1	Requirement review of the DSS-prototype's Functionality and Construction	67
6.2	The DSS-prototype Techno-economic Realizability	69
6.3	The DSS-prototype Socio-technical Impact	70
7	Conclusion & Recommendations	73
7.1	Conclusions	73
7.2	Recommendations	74
A	Selection Matrix for Corrosion Monitoring	77
B	Selection Matrix for Wear Monitoring	81
C	Corrosion Monitoring Techniques	85
D	DSS' Selection Process for EM - Remote Field Testing	89
E	CBM Applicability	101
F	Selection Process for Strain Measurements and Elastomer Compatibility Test	103
F.1	<i>Category [A]</i> : Attributes related to the sealing mechanism: . .	103
F.2	<i>Category [B]</i> : Attributes related to the supposedly selected CM strategy:	104
F.3	<i>Category [C]</i> : Attributes related to the wear mechanism	106
	Bibliography	107

List of Figures

1.1	Validation approach	4
1.2	Project Management Triangle	4
1.3	The design deliverable outline	6
2.1	The ease of change along the development phase	7
2.2	Deriving capabilities from scenarios	12
3.1	System's temporal- and hierarchical context	19
3.2	Feedback control for the system under design	21
3.3	Top-level view: functional view (left) ; physical view (right)	23
3.4	Design- and engineering cycle	25
3.5	The DSS interacting with its context	26
4.1	PF-curve [29]	32
4.2	Schematic overview of the selection matrix	33
4.3	NACE taxonomy of direct corrosion monitoring techniques	34
4.4	NACE taxonomy of indirect corrosion monitoring techniques	35
4.5	Selection process categorization [A21]	36
4.6	Selection process categorization [A22]	37
4.7	Selection process categorization [A23]	37
4.8	Selection process categorization [A31]	38
4.9	Selection process categorization [A32]	38
4.10	Selection process categorization [B11]	39
4.11	Selection process categorization [B12], [B13], [B15]	40
4.12	Selection process categorization [B14]	40
4.13	Selection process categorization [B2]	41
4.14	Selection process categorization [B3]	42
4.15	Selection process categorization [B4]	43
4.16	Selection process categorization [C]	44
4.17	Condition Monitoring Techniques for Wear [T]	46
4.18	Processing Techniques for Vibration Analysis in the time domain [T3]	47
4.19	Processing Techniques for Vibration Analysis in the frequency- [T4], the time-frequency- [T5] and the modal domains [T6]	47
4.20	Selection process categorization [A4]	48
4.21	Selection process categorization [A51]	48
4.22	Selection process categorization [A52]	49
4.23	Selection process categorization [A53]	50
4.24	Design- and engineering cycle	51
4.25	Expert System Architecture	52

4.26	Forward Chaining	53
4.27	Backward Chaining	53
4.28	The ES-based DSS outcome before filtering the fictive confidence variables	54
5.1	Design- and engineering cycle	57
5.2	Field signature method installation with protective cover . . .	58
5.3	Corrosion activity occurring in a straight geometry (tank's floor)	60
5.4	columns with corrosion damage	61
6.1	DSS' hierarchical structuring	68
6.2	Socio-technical environment	70
E.1	Decision scheme for condition-based maintenance applicability [22]	102

List of Tables

2.1	Stakeholders according to Alexander's taxonomy	10
2.2	List of stakeholders' (StR)- and systems' (SyR) requirements .	16
2.3	Expectation matrix	18
3.1	Design problem vs. knowledge question	24
3.2	stakeholders-, desires and goals	25
4.1	Guideline for CBM applicability for the system of interest . . .	56
5.1	Non-linear corrosion growth	61
6.1	The DSS' SWOT elements	71
C.1	CM- and NDT techniques' sub-categories	85

List of Abbreviations

CBM	Condition-based Maintenance
CM	Condition Monitoring
CrM	Corrective Maintenance
DSS	Decision Support System
ES	Expert System
FM	Failure Mechanism
FMECA	Failure Mode Effect and Criticality Analysis
IP	Innovation Projects
NDT	Non Destructive Testing
NIGC	National Iranian Gas Company
PvM	Preventive Maintenance
RBM	Risk-based Maintenance
RBR	Rule-based Reasoning
RCM	Reliability-Centered Maintenance
RE	Requirements Engineering
StR	Stakeholder Requirement
SyR	System Requirement
TPM	Total-Productive Maintenance
UT	University of Twente
WCM	World Class Maintenance

Chapter 1

Introduction

1.1 Background & Motivation

To sustain their optimal performance, systems and structures must be maintained and maintenance activities need to be performed. For this purpose, many companies adopt in general a preventive maintenance (PvM) strategy in order to keep their assets in an ideal condition. However, the challenges facing this strategy are organizationally puzzling in terms of scheduling. An appropriate length of the maintenance interval should be determined, if the maintenance interval is too short then the components are replaced before the end of their service life leading to high costs and waste of resources. On the contrary, replacing too late implies failures and therefore severe consequences might be expected. For those reasons, the actual condition of an asset needs to be monitored in order to regulate the appropriate maintenance interval [44] – hence, the implementation of the condition-based maintenance (CBM) policy.

However, performing CBM does not come without difficulties. Many sensors and processing techniques are nowadays available for condition monitoring (CM) and non-destructive testing (NDT) purposes [8], and selecting the most suitable ones remains challenging. In fact, this complex practice requires not only a full understanding of all existing CM- and NDT techniques, but an understanding of the asset under consideration, from a failure point of view, is equally crucial. Although a CM technique cannot improve practices, such as operating, installing and repair, it is able to improve the quality of inspection and consequently, if correctly carried out, identify failures at an early stage and by extension, improve the management of maintenance programs.

1.2 Objectives

1.2.1 Description of the design challenge

Despite the numerous advantages it represents, CBM is not always the best way of performing maintenance. PvM and corrective maintenance (CrM) have their advantages as well. Nevertheless, when CBM yields enough benefits, the identification of the right attributes will decide which approach,

in terms of selecting the most suitable CM strategy, could be attractive and what equipment the company needs to invest in. The effectiveness of the CBM policy strongly depends on the CM techniques available which then facilitates the path towards erecting a reliable business case to determine the financial feasibility.

1.2.2 Design Challenge

Design Problem

Providing that the CBM policy is applicable and that the criticality analysis issued a critical component, the diversity of the available CM techniques adds an additional challenge to the CBM's technical feasibility. Although multiple CM techniques might enable CBM effectively, the selection of the best CM techniques, or combination of techniques, can enable the CBM policy in both an effective and efficient manner. The present design project focuses mainly on providing a selection methodology by addressing the following design problem:

- *How can a suitable condition monitoring strategy be selected for a specific application, that enables efficient condition-based maintenance?*

The various disciplines that need to be dealt with during this design project are numerous, ranging from physical phenomena to technical understandings of CM strategies. For this purpose, certain aspects need to be addressed, resulting in two sub-questions:

Component selection: A component is suitable for CBM when considered "critical", in terms of safety and/or economy, and if a performed criticality analysis proves such. The complete knowledge of the selected component plays a vital role in conducting a successful business model.

- *Which of the identified (sub-)components are most suitable for being monitored?*

Technological feasibility: Following the identification of the critical component and the underlying failure mechanism, a suitable CM strategy should be designated.

- *What is the best condition monitoring strategy for a given application, its potential and limits?*

Main Objective

The design problem alluded to the actual design challenge. CM technologies are numerous and so are their characteristics. To consider all the inherent characteristics and translate them into compatible attributes, the CM

techniques should be compared from the same reference. The main objective of the design project is formulated as follows:

"All commercially available condition monitoring technologies and non-destructive testing techniques are to be brought together. This knowledge will be used to design a decision support system that advises in the selection of the condition monitoring strategy in a specific situation, and thus enabling the condition-based maintenance policy."

1.2.3 Approach

Understanding what needs to be done stands equally crucial to knowing what to do, including the activities within the so-called design/engineering cycle and their interdependencies. The synergy of such activities (presented in more detail in chapter 3) comes in three steps when considering the design cycle (and two additional steps when considering the engineering cycle). The first step consists of identifying the problem under investigation, i.e. enabling the CBM policy while disabling, when applicable, the other maintenance policies (e.g. CrM and PvM). To successfully tackle the investigated problem, requirements are designed and a clear state-of-the-art study (chapter 4) is carried out in order to be aware of the challenges and therefore facilitating the road towards a potential "cure" (i.e. second step: design phase) for this particular "illness" (i.e. the investigated problem) – this step is called the design phase. The next step is to validate the "treatment" (i.e. design solution) in question by mainly conducting case studies on one hand and interviews and brainstorm sessions on the other hand. The output of the validation phase is then used as input for the first step again, this is to adjust and optimize the selection method by making the system under design contextual. The more iterations, the more accurate the selection method gets. The accuracy is then measured, during each iteration, by complying the performances to the predefined requirements in chapter 2.

Although ultimately a selection methodology covering all possible applications is ambitioned, the design project prioritizes cases from the process industry where the main stakeholder is active. After validating the selection methodology based on experts opinion, multiple case studies will be executed enabling a divergent approach (i.e. from specific to generic) for addressing this problem. During this multi-case approach and based on the supposedly selected CM techniques, the selection methodology will be addressed, reviewed and reevaluated in an iterative way. Each iteration in figure 1.1 is expected to deliver eventual adaptations to the design until the selection methodology meets all the requirements established in chapter 2.

FIGURE 1.1: Validation approach

The design steps are carried out in collaboration with elements defined in the stakeholder-domain (e.g. because of the established stakeholder-domain, the requirements are defined accordingly). The need for the stakeholders to adapt and adjust and iteratively evaluate the outcomes is crucial, making the communication process (often proceeded by personal meetings, phone calls, e-mails) a vital component.

Project Management Triangle

Project Management is the application of a collection of tools and techniques to direct the use of diverse resources toward the accomplishment of a unique, complex, one-time task within three interrelated constraints [6]: (1) time; (2) cost and; (3) quality. Together the constraints form a triangle:

FIGURE 1.2: Project Management Triangle

In an ideal world, a decision should improve the product's quality whilst simultaneously reduce its cost and shorten the time needed for its development. Although the present design project has been initially set based on reasonable constraints (i.e. timeline, cost, quality), any set of unplanned or unexpected events can cause deviation from these constraints. To cope with an eventual change, trade-offs are expected to be made and every decision made should consider which of the constraints should be prioritized.

1.3 The Design Project Outline

The thesis is organized in seven chapters. Chapter 2 introduces the stakeholders in more detail and the limitations they impose, in the form of requirements, on the design project's main objective. This chapter elaborates the first step of the so-called design cycle of which the methodology is overly discussed in chapter 3. The remaining two steps of the design cycle concern chapter 4 and chapter 5 discussing the implementation and validation of the selection process, respectively. As for implementing the selection process, the notion of an expert system (ES) is reviewed. Next to the implementation phase comes the validation phase where the case-studies serve as a validation tool. The design deliverable is then outlined in chapter 6 and serves as an element for closing the loop within the design cycle. Finally, chapter 7 arrives at general conclusions while indicating directions for future research.

The system under design evolves throughout the chapters and so does its status during the whole design process (*fig. 1.3*). It starts from being termed a selection method(ology) in chapter 2, to an ES-based decision support system (ES-based DSS) in chapter 4, to a DSS-prototype in chapters 5 and 6.

FIGURE 1.3: The design deliverable outline

Chapter 2

Requirements Engineering

2.1 Introduction

At the beginning of the design process, freedom of making decisions is infinite leading to great uncertainties in the outcomes. The systems architecture has therefore to be defined in order to anticipate outcomes based on little information. As such, defining requirements takes place in the early phase of the design process where many decisions have to be made. At this early stage, a significant amount of design-related uncertainties exist (*fig 2.1*). As the design process progresses, the ease of change, in contrast with committed-to requirements, decreases rapidly along with the associated uncertainties [37].

FIGURE 2.1: The ease of change along the development phase

During this early phase of development, the opportunity to align the stakeholders' needs and requirements with the design challenge, stated in section 1.2.2, is provided. The aim is to qualify these stakeholders based on their needs and requirements, under the condition that they contribute to solving the design problem. Consequently, the opportunity to scope the main objective is possible rendering the design project as a whole more realistic. Moreover, the design approach (*sect. 1.2.3*) is expected to be facilitated by the same stakeholders and thus imposing, in certain cases, additional requirements. Engineering these requirements are the subject of the present chapter.

In systems engineering terminology, requirements engineering (RE) is considered a common concept. It refers to a process of discovering, developing, tracing, analyzing, qualifying, communicating and managing requirements that define a system at successive levels of abstraction [18]. Many aspects of systems engineering and project management are in relation with this discipline, including aspects such as (functional and performance related) requirements, needs and stakeholders. They interact at different levels, which are detailed in section 2.3.1, when transforming abstract needs into documented requirements.

2.2 Stakeholder Analysis

2.2.1 Main stakeholders

The Netherlands-based World Class Maintenance (WCM), the design project's main stakeholder, is a network organization of service providers, asset owners, research institutes and the government. The WCM organization is erected with one main objective: making the maintenance of the Dutch industry 100% predictable. This so-called, *smart maintenance*, is achieved by sharing the knowledge within the organization; developing new maintenance concepts and; applying them to real-world situations.

In addition to CBM-related topics [4, 11, 13], various innovation projects are carried out across other fields, such as: risk-based maintenance (RBM), design for maintenance [17] and performance-based contracting [21, 28].

The institutions associated to the WCM organization are active in one or more of the hereabove mentioned fields. They collaborate on such topics in innovation projects (IP) on an ad-hoc basis and in different consortia. The present design project was funded by the companies collaborating in the WCM-IP project on CBM. DNV-GL in particular alongside with Gasunie are part of the WCM-IP consortium and played an essential role in providing actual case-studies for the present design project.

DNV-GL is a multinational company headquartered in the vicinity of Oslo, Norway. It is active in several sectors, including the oil and gas sector. In Groningen, the Netherlands, DNV-GL has an office specialized in technical consultancy services to e.g. global oil and gas industry. The office works with upstream oil and gas companies, such as Gasunie, to improve safety and performance, assure reliability of a project's development and operation in addition to risk identification and control. Moreover, DNV-GL Groningen provides technical consultancy services to the oil and gas industry by combining technical, digital and operational expertise, risk methodology and in-depth industry knowledge.

Gasunie is an European asset owner active in the gas and oil sector. The gas infrastructure, owned by Gasunie, transports natural gas in the Netherlands and northern Germany. The infrastructure network is used by Gasunie's customer to the end-user for safe and reliable gas transportation. Among their operational assets: e.g. different types of valves and pipelines.

Outside the framework of the present design project, DNV-GL and Gasunie participated in a case-study. Gasunie installed a large number of valves in large gas transmission grids and are becoming, because of the ageing factors, increasingly unreliable. Therefore, Gasunie decided to replace these valves by new ones and estimated the cost of replacement to be approximately 1 billion euros (1 B€). Meanwhile, Gasunie realized that postponing such an operation for as long as possible would be financially beneficial - that is, the amount of money could be invested elsewhere during the time period where the operation would have been postponed. To this end, Gasunie collaborated with DNV-GL in order to come up with a solution that involves replacing the valves at its latest possible.

To solve this case, DNV-GL proposed to develop guidelines for CM systems that are able to isolate the valves that are most vulnerable, during the time where the replacement would have been postponed. Since the solution lies in CM, the next natural step is to identify what CM strategy is suitable for the valves in question. The selection methodology, which is developed in this design project, is a natural fit to the encountered problem confronted by both DNV-GL and Gasunie.

2.2.2 The Problem Domain

The *problem domain* is the domain in which the selection methodology is going to be used. It is in this domain that the operational aspect (i.e. advice in a suitable CM-strategy) along with the intended purpose (i.e. reduce overall maintenance costs) is expressed [18] by the *stakeholders*. To initiate a generic process for creating the stakeholder requirements, one should (1) identify these stakeholders; (2) create scenarios conceptualizing what the selection methodology might look like; and finally (3) scope the objective in section 1.2.2 based on how the involved stakeholders perceive the different scenarios.

Step 1 : The stakeholder domain

In jurisprudence, a stakeholder is considered as a legal body that refers to a human or non-human entity and has an interest or concern in a project [40]. It can affect or be affected by a number of actions, objectives and policies [38].

Following the taxonomy developed by Alexander [5], the stakeholders involved within the present design project are proposed. Table 2.1 introduces three classes of stakeholders, i.e. (1) stakeholders interacting with the

selection method; (2) stakeholders interacting with the context in which the selection method is placed; and finally (3) stakeholders that participated in developing the selection method itself.

TABLE 2.1: Stakeholders according to Alexander's taxonomy

<i>(1) Stakeholders interacting with the selection method</i>	
Normal operators	Decision-maker
Maintenance operators	UT CM experts
Operation operators	<i>none</i>
<i>(2) Stakeholders interacting with the immediate environment of the selection method</i>	
Functional beneficiaries	Decision-maker
Financial beneficiaries	WCM organization Case-study providers
Political beneficiaries	WCM organization
Negative stakeholders	Maintenance consultancy agencies Spare-part suppliers
<i>(3) Stakeholders developing the selection method</i>	
Sponsor	WCM-organization
Purchasers	Companies within the WCM organization
Developer	UT
Consultants	Supervisors CM-experts FM-experts

- *Decision-makers (i.e. end-user)*: They have a direct interest in the system's performance during a normal (or ordinary) operation. Their valuable insight and their opinion on how they would like to see the selection methodology being improved makes this category one of the most important stakeholders.
- *UT* : It has the responsibility for developing and operating the budget of the system under design.
- *WCM organization* : It has the responsibility for contributing to the funding of the system under design.
- *Case-study providers (e.g. DNV-GL and Gasunie)* : They have the responsibility for providing the design project case-studies in order to evaluate the requirements.
- *Maintenance consultancy agencies and suppliers*: Also known as negative stakeholders. They perceive the design project as a potential threat.

- *Supervisors*: They have the responsibility for reviewing and assessing the project's conformity to the organization's philosophy.
- *CM- and FM experts*: They make sure that the system under design is consistent with their respective fields of interest.

It is important to bear in mind that not all stakeholders (*tab. 2.1*) are equally accessible. Additionally, certain stakeholders (e.g. CM- and FM experts, and case-study providers) are accessible via other stakeholders (e.g. supervisors) and form a solid network with the design project might be crucial for its success. For example, corrosion as FM was selected as a result of the available expertise in this particular field. This availability was made possible thanks to the supervisors' network.

Step 2 : Create scenarios

Each stakeholder perceives the design project's objective differently, that is, various scenarios can be anticipated depending on the stakeholders' perspective. In fact, certain scenarios are seen as beneficial for certain stakeholders as they promote their proper understanding and communication. Therefore, all stakeholders that do not have their objective aligned with the design project's are disqualified.

To anticipate the different scenarios (*fig. 2.2*), the scope of the design project is set to meet the "*ambitious*" design project's objective (*sect. 1.2.2*). The selection methodology should be contextualized in order to determine an agreed-upon boundary and set a much more realistic scope once and for all. Initial estimates can then be made based on possible scenarios to give a general idea of whether the design project as a whole would be feasible. Anticipating these scenarios results in (1) a guidance that *qualified* stakeholders could provide during the operational use of the system under design ; and (2) any missing detail can be later on converted into a *need* and from which a *set of requirements* can be drafted.

FIGURE 2.2: Deriving capabilities from scenarios

This means that all stakeholders should have agreed ground rules (i.e. they must perceive the same scenarios depicted in figure 2.2) and the absence of such an agreement would be unproductive. For instance, potential case-study providers indicated a desire towards a selection methodology for CM technologies enabling risk-based maintenance (RBM). If agreed-upon, the scope of the design project can be narrowed accordingly. Assuming that such scenario aligns with the project's main objective, the potential stakeholders might align their interest with the project's - and if not, the scenario will be discarded along with the potential stakeholder that provided such scenario. In the present design project, the RBM scenario has been discarded.

Step 3 : Scope the objective

The scenarios based on the stakeholders' wishes and needs play an essential role in defining the scope of the design project. Following multiple interviews, events and meetings, the design objective (*sect. 1.2.2*) came to restrict itself to the stakeholders' needs. The following stakeholders were part of this process: (1) case-study providers and WCM organization; (2) UT; (3) FM experts; (4) CM experts.

1. A selection method covering all possible applications is ambioned, yet the design project prioritizes case-studies from the process industry since the case-study providers are active in this sector.
2. The critical components experiencing unavoidable loads are assumed to be known for the application under consideration, as the critical part selection process is considered to be too extensive to be included in the two-year design project.

3. The aim of the design project is to include all FM under which a critical component fails. However, the way the stakeholders are involved within the design project prioritizes two failure mechanisms, i.e. the corrosion- and the wear mechanism.
4. The aim of the design project is to include all CM- and NDT techniques that are commercially available. However, the FM scope is restricted only to corrosion and wear and therefore, only CM- and NDT techniques compatible with these failure mechanisms are within the scope of the present design project. Moreover, the commercial aspects of these techniques such as quality, size and brands are not included in this study.

2.2.3 The Solution Domain

The *solution domain* is the domain where the set of stakeholder requirements, as generally described in the *problem domain*, are understood and further derived into system requirements. It is in this domain that the question to "*how to advise in a suitable condition monitoring strategy?*" should eventually be answered. However, the components that work together in order to achieve the overall purpose must be treated as "black boxes" and first ensure "*what they are required to do*" before getting into detail on "*how to achieve what is required in the problem domain?*". In order to avoid the tendency to go too much into detail, an abstract system model must be created that encompasses [18] the following:

- The internal functionality exhibiting what must be done by the selection methodology: Advise in a suitable CM strategy.
- The functionality enabling the selection methodology for a substantial interaction with its environment: Integrate the CBM policy within the company's maintenance program, by developing a decision support system (DSS) for CM technologies.
- The functionality preventing the selection methodology from malfunctioning: Assert a certain amount of reliability and maintainability.

Compartmentalizing the solution domain into abstract system models, where each model is responsible for answering a specific functionality, helps structuring the problem domain by providing specific solutions to specific problems without redundancy. For instance, the function that asserts a certain amount of maintainability would be quite different from the function that exhibits what must be done in the first place. In fact, asserting DSS' maintainability requires a different solution than having the DSS advise in a suitable CM strategy.

2.3 Writing & Reviewing Requirements

According to INCOSE [34], a guide for writing requirements, needs and requirements exist at five levels (*sect. 2.3.1*). The "enterprise" level hovers at the top where enterprise strategies, in the form of needs, are for the first time expressed. The transformation of needs into requirements takes place in the four remaining levels (i.e. the business management level, the business operations level, the system level and finally the system element).

2.3.1 Transformation of needs into requirements

The Enterprise level

According to ISO/IEC 29148, the operational concept describes what the system will do (not how it will do it) and why. It is used to communicate overall quantitative and qualitative system characteristics to the acquirer, user, supplier and other organizational elements. The Enterprise level sets the strategies of the present design project as follows:

- *what*: enable the CBM policy
- *why*: reduce overall maintenance costs

The ultimate need is to develop general guidelines facilitating CBM for critical applications with the aim to reduce maintenance activities and thus the overall costs related to maintenance (e.g. maintenance personnel, spare parts, repairs, unnecessary maintenance interventions).

The Business Management level

In this level, the operational concepts previously defined are further developed into business needs, goals, objectives and constraints [34]. The system's characteristics and business requirements are subsequently derived and formalized in a preliminary life-cycle concept and is based on the following:

- *the acquisition concept*: shapes the stakeholders' engagement (*tab. 2.1*), the selection's method and its development, and finally the verification procedure. This section will be further detailed in the design cycle (*fig. 3.2.2*) in chapter 3.
- *the deployment concept*: describes the approach of validating, delivering and introducing the selection methodology into operations. This section will be further detailed in the engineering cycle in chapter 3 (*sect. 3.2.3*).
- *the support concept*: outlines the support infrastructure (i.e. manpower in terms of operating, engineering, maintenance and training) once the selection methodology is deployed. This section will be further detailed in chapter 5.

- *the retirement concept*: describes the way the system will be decommissioned.

The Business Operational level

In this level, the preliminary life-cycle concept is elaborated by engaging the stakeholders. Together with both the Enterprise- and the business management levels, the Business operational level is considered to be in the problem domain where the respective needs and requirements are defined.

The (sub)system level

The (sub)system level, in which the selection methodology is defined in logical and physical views, is responsible for transforming the stakeholders' needs and requirements into systems' needs and requirements. The (sub)system level is considered to be in the solution domain where the respective system needs and requirements are defined.

While the problem domain (i.e. the business levels) focuses on *what* the selection methodology is able to do; *how* well should the selection method comply with the predefined requirements; and *why*, the solution domain's (i.e. (sub)system level) focus is on *how* the problem should be solved; *how* would it look like once the selection methodology has been implemented. The (sub)system level sets the strategies of the present design project as follows:

how : design a selection method that advises in suitable CM-strategies and thus enables the CBM policy

2.3.2 List of requirements

The stakeholders'- (StR) and systems' (SyR) requirement specifications are intended to represent different sets of requirements. The former answers questions ("*what should be done?*", "*how well should it be done?*" and "*why is it done?*") related to the business level, and the latter defines ("*how is it solved?*") at the system level.

A complete overview of the requirements is provided in table 2.2. These requirements have been derived using the levels described in the INCOSE approach. The set of stakeholder requirements and the corresponding system requirements are organized in categories under the same name. The numbering within each category links the requirement specifications of both the business- and systems level, if applicable.

TABLE 2.2: List of stakeholders' (StR)- and systems' (SyR) requirements

Category	Label	Description
General	StR 1	The selection method shall be utilized by decision-makers (e.g. managers and maintenance staff) that have access to information related to the system to be monitored and to the failure mechanism under which it predominantly fails.
	StR 2	The selection method shall comply with the input provided by the decision-maker.
	StR 3	The selection process shall follow the criticality analysis upon which the critical component has been identified.
	StR 4	The identified critical component undergoes the mechanism-based failure analysis and shall precede the selection process.
	StR 5	The selection process shall proceed only and only when the critical component along the influencing factors have been identified, studied and analyzed.
	StR 6	The selection process shall proceed only and only when the predominant failure mechanism underlying the critical component's failure has been identified, studied and analyzed.
Applicability	StR 7	The selection method shall be suitable for applications within the process industry or industries sharing similar kind of applications.
	StR 8	The selection method shall be suitable for applications eligible only to CBM.
	StR 9	Selected CM- and NDT techniques for purposes other than facilitating the CBM policy shall not be included in the selection methodology (e.g. CM-technologies for safety concerns).
Financial feasibility	StR 10	The selection method shall enhance the decision-maker's ability to build business cases.
	StR 11	If one CM- or NDT technique has been issued from the selection methodology, a single business case is erected to assess the financial feasibility of this particular technique.

Continued on next page

Table 2.2 – Continued from previous page

Category	Label	Description
	StR 12	If two or more CM- and/or NDT techniques have been issued from the selection methodology, multiple business cases are erected to assess all possible combinations of the selected techniques.
Technological feasibility	StR 14	The selection method shall facilitate the decision-making process by providing advice in CM- and NDT techniques that are technologically mature.
	StR 15	The selection method shall facilitate the decision-making process by providing advice in CM- and NDT techniques that are commercially available.
	StR 16	The selected CM-technologies shall not entail further modifications on the system to be monitored (e.g. redesign)
	StR 17	The selected CM- and NDT techniques shall not hinder the monitored system's ability to perform its function.
	StR 18	The selection method shall interact with the decision-maker's manual input. The output, however, shall be provided automatically by the selection method itself.
Maintainability	StR 19	The selected CM- and NDT techniques shall not be outdated.
Readability	StR 21	The decision-maker shall be able to follow and comprehend the instructions provided by the selection method.
	StR 22	The decision-maker shall be able to trace back the reasoning behind the advice obtained from the selection method.
Scalability	StR 23	The decision-maker shall have access to the selection method user interface on his own platform.
Technological feasibility	SyR 18	The selection method shall come in the form of a decision support system (DSS).

Continued on next page

Table 2.2 – Continued from previous page

Category	Label	Description
Maintainability	SyR 19	The selection method's knowledge base shall be accessible for update.
	SyR 20	The selection method shall be accessible by CM- and FM experts for maintenance and upgrading related purposes.
Readability	SyR 21	The validated selection method shall be accompanied with complementary information for guidance. The guidance contains information about relevant literature, operating conditions, training courses, maintenance and engineering.

The next chapter puts an emphasis on the design cycle as a whole. As for the needs and their formal transformation into requirements (*tab. 2.2*), the motivation is firstly provided in the first step of the design cycle. During the remaining steps of the design cycle, it is important to constantly consider the stakeholders' overall expectations and frustrations. It evolves around the following (*tab. 2.3*):

TABLE 2.3: Expectation matrix

Expectation factor	enabling CBM
Expect to give	investing in eventual CM technologies
Expect to receive	reducing maintenance-related costs
Frustration factor	conservatism towards traditional maintenance policies

As for maintaining a proper mental support, the expectation matrix depicted here above, displays what factors should constantly be considered during the design process. Stakeholders are motivated by the "expectation factor" whereas they tend to give less and receive more. To put this in the right context, the present design project should put an emphasis on CM strategies that lead to profitable investments (i.e. minimize "expect-to-give" component of the expectation matrix while maximizing its "expect-to-receive" component). Alleviating the frustration factor (i.e. conservatism) is another factor one should focus on, as it allows the removal of any potential ambiguity that might hinder the advancement of the project.

Chapter 3

Design Methodology

3.1 Systems thinking

A system design tool, such as the 9-windows technique (*fig. 3.1*), is a tool that can support the thinking tracks. It puts the system under design in its temporal and hierarchical context [35]. On the horizontal axis, the temporal context displays, from left to right, the perceived past of the system under design, the present situation, and the envisioned future, respectively. The vertical axis describes the hierarchical context in which the artifact is placed or to be placed. The lower- and higher hierarchical levels correspond to the artifact's sub- and super-system, respectively. The middle corresponds to the same hierarchical level at which the system under design is placed.

FIGURE 3.1: System's temporal- and hierarchical context

The context in which the system under design is placed plays an essential role in solving the encountered design problem. Such a tool enables systems thinking on a multidisciplinary level. When placed in its hierarchical environment, the system under design (system) has to be compatible with the actual maintenance program (super-system). In other words, the maintenance program should include CBM as an acceptable maintenance policy allowing for the supposedly selected CM techniques (sub-system) to be employed on critical components only. Nowadays, CM techniques are subject to financial- and technological restrictions before any implementation can take place. As technology evolves, many CM techniques become even more mature rendering the future expectations of a supposedly selected CM strategy restricted to financial concerns only. Consequently, a

broader spectrum of CM techniques can be selected.

Now that the system under design is contextualized, it is imperative that all related knowledge and information in the problem domain is explicit. The relation between the system under design and the infrastructure in which it is placed is established. Meanwhile, the compartmentalized transition to the solution domain is thorough by bringing in the twelve thinking steps. In principle, the twelve thinking steps provide a structured way for finding solutions and ensuring that all aspects of the problem domain are covered without redundancy.

The twelve thinking steps are elaborated in the following order [37]: (1) dynamic thinking; (2) feedback thinking; (3) specific-generic thinking; (4) scales thinking; (5) scientific thinking; (6) decomposition-composition thinking; and (7) hierarchical thinking. Then (8) life-cycle thinking (*sect. 3.2.2*) and (9) risk thinking (*sect. 6.3*) are discussed separately. The remaining three steps, i.e. (10) operational thinking ; (11) project thinking and (12) safety thinking are not discussed in the present design project as they have nothing or little to do with the system under design.

Dynamic Thinking The time dimension in the 9-windows diagram depicted in figure 3.1 consolidates the fact that the system under design is interacting in a changing environment. Both the maintenance program (super-system) and the CM technologies (sub-system) are susceptible to change with time forcing the system to change accordingly. The observable changes in the system's environment can help anticipate unexpected effects. As for the present system under design, it must contain an exhaustive list of already existing CM- and NDT techniques. As the environment evolves with time, the system under design must be able to cope with upcoming CM technologies.

Looking at the system under design from a dynamic point of view is also (1) to evaluate how it changes over time and (2) to assess the effects when changing the input/output. The use of different time-scales might be of use:

- **seconds:** a decision-maker providing his answer to the system (i.e. readability)
- **minutes:** a decision-maker obtaining the possible set of combinations for selected CM techniques (i.e. traceability - if, for example, no advice is provided)
- **days:** a decision-maker evaluating a suitable CM strategy (i.e. financial feasibility)
- **months to years:** a decision-maker having access to new CM techniques (i.e. maintainability)

Feedback Thinking The dynamic behaviour of the system's environment requires an output (i.e. advice in a suitable CM strategy) being constantly evaluated against the corresponding inputs (i.e. answers provided by the decision-maker). Comparing the *obtained* output with the *desired* output by adjusting the available controls (i.e. technical feasibility : this can be manipulated by an expert system for example) introduces the concept of a basic *feedback control*. In creating the output, the system's performance is measured by a so-called "measurement system" (i.e. applicability: multi-case study) that evaluates the acceptable error ϵ (i.e. measurability: a decrease in overall maintenance costs) between *desired*- and the *obtained* output.

Figure 3.2 illustrates the feedback concept the present design project is opting for:

FIGURE 3.2: Feedback control for the system under design

Specific - Generic Thinking Specific-Generic thinking restricts the scale of the problem to the corresponding solution it represents. Although ultimately a selection method covering all possible applications is envisioned, the system under design prioritizes cases from the process industry sector (i.e. applicability: cases under study for which testing and measuring the overall performance of the system under design is suitable). Other sectors sharing similar kind of applications are also eligible for the system under design. As such, a given application consists of various (sub-)components causing the monitoring process to be impractical if the most critical (sub-)component is not identified (i.e. applicability). All in all, an iterative design approach, of carrying out case-studies, facilitates a divergent approach allowing additional applications, and the corresponding critical (sub-)components, to be included extending the scale of the problem to more eligible solutions.

Scales Thinking The number of companies that are willing to invest in tools facilitating the practice of CBM is rising. Even more so, when organizational constraints (such as conservatism) are overcome and the

system under design is extended within the primary sector, a scaling has to be made (i.e. scalability). Originally, the intelligence behind the selection method would be a set of "if-then" rules able to act in exclusive environments. With the increasing number of users, accessibility might be of concern (i.e. scalability). In principle, the selection method is therefore to be designed under two main parts: the logic of the decision making process, and the user-interface part. As the logic part remains the same regardless how it is distributed, the user-interface part can be delivered as a client-side Java applet, a servlet via a HTML form, or a stand-alone application.

Scientific Thinking In systems thinking, it is important to use scientific principles by appropriately formulating the theory and derive a hypothesis. A verifiable model can be obtained in order to test and measure the performance of the formerly derived hypothesis (by consulting experts and literature). In the present case, increasing the number of measurements improves the accuracy. The iterative nature of a given measurement is to be performed by the means of a case-study. It must be a verifiable method allowing adjustments to be made with each iteration until the ultimate form of design is obtained, that is, by fine-tuning the "if-then" rules.

Decomposition-Composition Thinking The primary function of the system under design is to *"advise in a suitable CM strategy"*. The intelligence behind the selection method is tested, verified and adjusted by consulting literature and experts. By adhering to the scientific thinking step, a successful advice, in a suitable CM strategy, requires not only a solid understanding of the existing CM technologies but the application to be monitored and the mechanism under which it fails need to be comprehended as well. Therefore, the top-level function has to be divided into sub-level functions creating interfaces during the process. These interfaces need to be put together despite the potential dissimilarities (e.g. all aspects of the general category in the requirements list in table 2.2 are to be brought together). For instance, the knowledge provided by the sub-functions related to the failure mechanism can be diverse ranging from mechanical- (e.g. wear, fatigue, static overload) and electrical- (e.g. electric failures), to chemical (e.g. corrosion) phenomena. In certain cases, the failure mechanisms can be presented as a combined form of different phenomena (e.g. erosion-corrosion, corrosion-wear, fatigue-wear). It is therefore essential to decompose the system accordingly and thus defining an appropriate interface between the subsystems. In addition to the sub-functions related to the failure mechanisms, the remaining two sub-functions are related to the critical component to be monitored (the system of interest), and the operating conditions under-which the supposedly selected CM strategy is to be placed. Each of these sub-functions require different literature/expert background leading to an organized decomposition of the system. In total, three sub-functions are identified, namely:

- *sub-function 1*: identify attributes related to the critical component,

- *sub-function 2*: identify attributes related to the operating conditions under-which the supposedly selected CM strategy is to be placed,
- *sub-function 3*: identify attributes related to the failure mechanism underlying the critical component's failure.

Hierarchical Thinking Hierarchical thinking is about ranking authority, facilities and priorities of the system's parts. It is known that the number of issues explodes when going from the initial system requirements to implementation details. The system partition in figure 3.3 lays out the top-level view from which the present design project is perceived. Two layouts can be distinguished: the functional view and the physical view: the first describes in eight steps "*what*" should hierarchically be done and the second indicates "*where*" in the system the functions should be performed. Figure 3.3 illustrates the eight steps of the functional view. Each step is placed in such a way that the levels from the physical view are aligned with those from the functional view.

FIGURE 3.3: Top-level view: functional view (left) ; physical view (right)

3.2 Design Methodology

3.2.1 Introduction

The design solution that the system under design provides has an organizational character as it tries to advise in the most suitable CM strategy with the aim to optimize traditional maintenance programs. As such, the context in which the system under design is placed depends on factors that are difficult to change (e.g. CM- and NDT technological maturity,

reluctance towards investing in CM- and NDT techniques, conservatism towards traditional maintenance programs). A subjective way of dealing with the "*design problem*", in its inflexible environment, is to address the corresponding "*knowledge questions*". The answer to the knowledge question must however be objective regardless the constraints imposed by the environment. The Table 3.1 illustrates how the *design problem* related to the present design project is motivated by the *knowledge question*.

TABLE 3.1: Design problem vs. knowledge question

Design problem	Knowledge question
Design a selection method able to advise in suitable condition monitoring strategies!	Is the selection method able to facilitate the condition-based maintenance policy?

3.2.2 The Design Cycle

The design cycle in figure 3.4 consists of three steps, namely:

1. the problem investigation,
2. the design phase,
3. the validation phase.

In a design cycle, each step is iteratively evaluated with every cycle that recommences. The engineering cycle encloses the design cycle on a larger scale and contains two additional steps, namely,

4. the implementation phase,
5. the evaluation phase.

Step 1: Problem Investigation During this step, it is necessary to collect and analyze field data from actual implementations (i.e. in this case, the implementation of the CM strategies) with the aim to find out what exactly needs to be improved and why. In this utility-driven project, the need to accurately select the suitable CM strategy is the issue that needs to be improved. Moreover, by referring to the stakeholder-domain (*sect. 2.2.2*) on the business level, answers to the so-called *knowledge questions* related to the stakeholders and their desires can be provided. These desires should be more or less aligned with the project's main objective (*sect. 1.2.2*). However, some desires might not be fulfilled because of the limited resources. Therefore, promoting these so-called *desires* into stakeholder goals is central to the project's success. Table 3.2 displays the stakeholders' desire being, or not being, promoted into stakeholder goals:

FIGURE 3.4: Design- and engineering cycle

TABLE 3.2: stakeholders-, desires and goals

Stakeholder desires	Stakeholder goal
Advise in the most suitable maintenance policy (e.g. CrM, PvM, CBM)	<i>demoted</i>
Enable CBM for critical components experiencing unavoidable loads	<i>promoted</i>

The stakeholders' desire is promoted into a stakeholders' goal (*sect. 2.3.1*) and is made possible by combining the analysis of both the stakeholders' and the systems' requirements (*sect. 2.3*). These requirements are generated from the initial stakeholders' need and have enabled an awareness for the goal by setting aside indifferences, fears and even demoted desires. Goals that do not correspond to the categories of requirements defined in table 2.2 are demoted. As a result, awareness arises from the fact that the stakeholders are not only familiar with the problem under investigation, but also with the provided solution in terms of design, validation, implementation and evaluation. Consequently, appropriate resources (time and capital) can be committed to evaluate and act for the agreed-upon goal, i.e. the goal of enabling CBM for critical components experiencing unavoidable loads. Once all stakeholders are on the same wavelength, a formal transformation from needs into requirements can be drafted (*tab. 2.2*).

Step 2: Design Phase The design solution facilitates the interaction between the system under design and the maintenance program. In design

engineering terminology, the system under design is known as "the artifact", and the maintenance program as "the context". Many other components of the context are present and are shown in figure 3.5.

FIGURE 3.5: The DSS interacting with its context

During this step, decisions about what to do with the system under design are made with the documented requirement specifications (*sect. 2.3.2*). These specifications should contribute to the ultimate goal, i.e. enable CBM for critical components experiencing unavoidable loads, defined in the previous step. Once the agreed-upon requirements are decided in step 1, discussions about potential solutions can then be initiated.

Potential solutions After the ultimate need in creating a selection method bringing all CM technologies together is expressed, the idea is explored and elaborated in accordance with the identified stakeholders and so are the potential solutions. Before the design phase is launched, a set of solutions is proposed and discussed (product life-cycle thinking).

Potential solutions are made based on the requirements developed in the initiation phase. In the design phase, multiple strategies are studied with which the project can achieve the intended results (i.e. stakeholder goal in table 3.2). The first design option was based on data-mining techniques (e.g. Weka: Data mining software in Java), the second was about direct programming on platforms such as Matlab, the third option was oriented towards techniques involving case-based reasoning approaches and the last option involved techniques implying rule-based reasoning techniques (e.g. Exsys Corvid : Expert System software). These potential solutions are evaluated against their pros and cons, and the optimum design solution is then selected for further studies that will ultimately lead to a design validation.

The potential solutions are then suggested, namely, those based on (1) data-mining techniques; (2) classical programming; (3) case-based reasoning approaches; and (4) rule-based reasoning approaches. Among these potential solutions, only one is selected for the next design step, i.e. the *Validation Phase*. Meanwhile, the selected design solution should comply with the stakeholders' commitment in terms of time, the agreed-upon cost and the quality (i.e. the project management triangle (*sect. 1.2.3*)). Some of these aspects are more restricted than others: for example, the time needed (two years) for accomplishing the present design project has little tolerance for being extended at the cost of the two remaining aspects. As such, any eventual deviation from the agreed-upon cost and quality should be consulted with the corresponding stakeholders, bearing in mind that these project management aspects are highly interrelated.

To this extent, the first and second available design solutions have been excluded since a software like Weka or Matlab do not include a user-interface platform and building one would be time-consuming. The third option, the case-based reasoning approach, has been excluded as well, this is due to poor literature presence dealing with CM- and NDT techniques facilitating CBM - consequently, a design solution of low quality might be expected. The remaining design solution uses techniques that are based on a set of "if-then"-rules and a strong literature presence allowing these rules to exist is available (*chap. 4*). Moreover, an expert system such as Exsys Corvid contains an inbuilt user-interface platform allowing it to be properly used in one of the next product life-cycle phases, i.e. the deployment phase.

Step 3: Validation Phase The aim of validation phase is to predict how the system under design, in the form of a prototype, will interact with its context (*fig. 3.5*), without being implemented. The prototype is exposed to expert opinions and/or to various scenarios in the form of a multi-case study based on literature where the requirements specified for the selection method (*sect. 2.2*) are evaluated.

The literature-based case-studies (*sect. 5.1*) and the documented case-study (*sect. 5.2*) serve as a validation tool for testing the prototype's performance, that is, the degree of compliance with the specified requirements. The documented requirements that the selection method must satisfy can be clustered, according to the architecture dimension, into three categories:

- *The physical system architecture* is responsible for validating the documented stakeholder requirements (*req. StR1 to StR23*). These requirements are related to the prototype's physical performance itself including the required infrastructure, e.g. scalability.
- *The software architecture* is responsible for validating the "if-then"-rules embedded within the selection method. The documented systems requirements related to this layer of architecture (*req. SyR18 to SyR21*) are the reference for measuring the performance of the "if-then"-rules, e.g. maintainability, updateability and readability.

- *The social architecture* is responsible for the validating both the prototype's social aspects of both the context (e.g. organization and decision-makers) and the selection methodology itself (e.g. training, user procedure, maintenance program). (*req. StR21 and StR22*)

Opinion-based validation method [45] , also called "expert opinions". The benefit of CM- and FM experts as stakeholders interacting with the DSS-prototype is straightforward. This opinion-based research method is the simplest way of validating the logic behind the selection method, and is useful as long as the CM- and FM experts are available. Having the DSS-prototype submitted to a panel of experts to imagine how it will interact with its problem context and to predict the effects. These effects should meet the documented requirements specifications mentioned in *step 2* - if not, a redesign of the prototype must be considered.

Literature-based case-studies [25] is a historical and observational validation method. It is intended to perform a multi-case study enhancing, during each iteration, the design solution leading eventually to more accuracy. Each iteration is expected to deliver eventual adaptations until the design solution meets all the requirements agreed-upon (*fig 1.1*). As such, the present design project iterated three case-studies based on literature (*sect. 5.1*) and one documented case-study (*sect. 5.2*).

Closing the design loop The design cycle commences its first loop when the prototype has proven a certain degree of compliance against the experts opinions, and the literature-based case-studies' outcome adhere to the requirements. This iterative approach is perfected during each loop where the corresponding outcomes converge more and more towards the documented requirement specifications (*sect. 2.2*), that is, the design project deliverable functional performances (*sect. 6.1*) are measured.

3.2.3 The Engineering Cycle

Step 4: Implementation Phase The engineering cycle starts when the design cycle is assumed to be (near-)perfect, that is, the agreed-upon requirements have all been reviewed together with stakeholders that are developing and interacting with the DSS-prototype (i.e. consultants and decision-makers (*sect. 2.1*)). Once outside the scope of the design cycle, the design solution moves from being a *prototype* to a *prototype under implementation*. Implementing the prototype is achieved by transferring it to the problem context itself (*fig. 3.5*) (i.e. maintenance program, organization and people, budgets). The ability to move from a CBM-free maintenance program to a maintenance program containing the CBM policy is the first step towards implementing the prototype in its context. For this to happen, implementing CBM should be financially justifiable.

The CM financial feasibility: The CBM policy and the CM technologies are intrinsically related. The CBM policy cannot be implemented, and by extension the prototype, if the selected CM- and/or NDT techniques are not provided. The system under design advises in CM- and NDT techniques that are technologically mature and once the techniques are selected, the decision-maker is able to form a CM strategy by bringing together the selected techniques in all different combinations. As such, a number of business cases can be erected where each combination of techniques can be evaluated against a potential implementation. The number of potential business cases is expressed by the following equation:

$$N = \sum_{k=1}^n \binom{n}{k} \quad (3.1)$$

where N is the number of business cases that can be erected, k is the index and n is the number of CM techniques that the system under design has advised in.

Suppose that the system under design has advised in a collection of three CM- and/or NDT techniques composed of technique A, technique B and technique C. This means that $\sum_{k=1}^3 \binom{3}{k} = 7$ different combinations exist and thus 7 different business cases can be performed. The optimal CM strategy, in terms of financial feasibility, must not be compromised from a technological point of view.

Step 5: Evaluation Phase In the engineering cycle, the evaluation phase (*step 5*) is contrasted with the validation phase (*step 3*) and is performed after implementing the prototype (*step 4*). The aim is to investigate how the implemented prototype is observed by the stakeholders after being validated.

Closing the engineering loop is similar to closing the design loop but on a broader scale. Each iteration adds additional value to the DSS under evaluation. By closing the engineering loop, observational case-studies are usually performed [45].

Note that the engineering cycle is outside the scope of the present design project.

Chapter 4

Designing the Decision Support System

4.1 Introduction

Many definitions of condition monitoring (CM) include it as being part of a maintenance activity [7, 24, 33]. On- or offline CM is a type of maintenance inspection where an operational asset is monitored and the data obtained analyzed to detect signs of degradation, diagnose cause of faults, and predict for how long it can be run safely or economically. However, the scope of the present review includes only the *technological* aspects of CM technologies. Economic- and safety-related aspects can be assessed independently once the technologically-feasible CM technologies are identified.

The selection of a suitable CM strategy depends on identifying measurable indications of a deteriorating machine or component [14]. Therefore, understanding the machine or component to be monitored (the system of interest), from a failure point of view, is a crucial step in assessing which CM strategy is optimum during the selection process. Although many failures are not age related, most of them give an indication of a deteriorating process going on. If evidence of such deterioration can be found, it may be possible to proactively act and eventually prevent costly failures. The final stages of a given failure can be illustrated by a PF-curve (*fig. 4.1*) where point **P** is the point where the deterioration becomes observable. If no action is undertaken, the condition continues to deteriorate until it reaches a point where a functional failure takes place (point **F**).

FIGURE 4.1: PF-curve [29]

Meanwhile, all existing CM technologies belong somewhere on the PF-curve. However, depending on what kind of system is being monitored, CM technologies inherently possess a number of potentials and limitations and can widen or shorten the PF-interval accordingly. The larger the PF-interval is for a particular CM technique, the more potential it has for forming a suitable CM strategy.

To achieve such performances, the technologically feasible CM techniques are selected based on selection matrices which attributes' are detailed in the present chapter for two failure mechanisms, namely, corrosion and wear. These selection matrices for corrosion (*app. A*) and wear (*app. B*) are constructed from the literature. Their rows represent all commercially available CM technologies and their columns represent the attributes associated to those CM technologies. Once a given attribute is selected during the selection process, the corresponding CM technology can either be (1) filtered out; (2) recommended; or (3) neutral. By evaluating the attributes against the available options, a synergistic CM strategy can be obtained. Within this context, decomposition-composition thinking (*sect. 3.1*) is employed to group these attributes into three main categories, namely:

- **Category [A]** : attributes related to the system of interest,
- **Category [B]** : attributes related to the supposedly selected CM technologies, their characteristics and the potential and limitations they inherently possess,
- **Category [C]** : attributes related to the failure mechanism itself.

Bringing this knowledge together in a certain order creates unique logic paths, each leading to a particular CM technique (*category [T]*). A schematic overview of the selection matrix is given in figure 4.2.

FIGURE 4.2: Schematic overview of the selection matrix

The attributes are organized in the coming sections according to categories [A], [B], [C] and [T]. A (sub-)attribute belonging to one of these categories is designated with the same letter followed by an exclusive numbering system.

4.2 Corrosion Monitoring

Corrosion monitoring refers to (continuous) corrosion measurements performed under industrial or practical operating conditions [32]. The assessment of corrosion and the related field parameters is a complex practice because of the diversity of applications, environmental conditions and fluid phases within industrial plants [31]. As such, the understanding and control of corrosion-related failure modes and their effects is generally poor [1]. It affects structural systems such as pipes and bridges. To this end, a number of techniques are developed: some are exclusive to certain applications, others are reserved for a number of fluid phases and conditions. As all corrosion monitoring techniques have their strengths and weaknesses, an ideal CM strategy is commonly set so that the weaknesses of one are compensated for by the strengths of another.

4.2.1 Category [T] : Corrosion Monitoring Techniques

A wide range of corrosion monitoring techniques (*app.* C), clustered within categories (*fig.* 4.3 and 4.4), are reported by the NACE International

committee in its technical report [31]. The report provided an overview of the characteristics of the corrosion monitoring techniques, their limitations and benefits. The categories, as described by the report, have been adjusted to the design project's purpose. However, two main classes of corrosion monitoring techniques can be distinguished: direct- and indirect techniques:

Direct Measurements: Corrosion monitoring techniques that fall into this class of techniques measure a corrosion-related parameter changed *directly* by the corrosion mechanism. It can be further divided into sub-categories (fig. 4.3).

FIGURE 4.3: NACE taxonomy of direct corrosion monitoring techniques

Indirect Measurements: Corrosion monitoring techniques that fall into this class of techniques measure a corrosion-related parameter changed *indirectly* by the corrosion mechanism such as presence of certain gases that might be produced from a corrosion-related reaction. This sub-category can be further divided into online- and offline techniques (fig. 4.4).

FIGURE 4.4: NACE taxonomy of indirect corrosion monitoring techniques

Within certain clusters of techniques, further sub-categorizations can be made. Even though differences are small, the selection process can be based on such differences and hence, ultimately lead to a suitable monitoring strategy.

4.2.2 Category [A] : Attributes related to the system of interest

In practice, it is important to understand the monitored system before engaging in any monitoring program. The choice of the corrosion sensors and methods depend on such knowledge as it facilitates the filtering process of all corrosion monitoring techniques that do not cope with features of the system of interest. For corrosion, such features are described by three attributes: (1) accessibility; (2) contact environment; and (3) material composition.

[A1]: Accessibility Accessing the system of interest can be done in two ways, namely, by accessing it physically (e.g. by unearthing, by disassembling, etc.) and/or by extracting representative sample.

[A11] : Physical Accessibility The choice of monitoring points is restricted by the existence of suitable access points [32]. In fact, not all monitored systems are equally accessible for corrosion monitoring techniques and it is therefore important to assess the extent to which the system of interest is physically accessible or, alternatively, to what extent is the system of interest in the state of increasing its degree of physical accessibility. The sub-attribute [A11] concerns parts of the monitored system where the corrosion interface takes place.

[A12] : Accessibility by sample-extraction The choice of accessing the system of interest by extracting samples is not only dictated by the existing sampling points (or introducing them in the eventual case), but to

the representativeness of this particular sample as well. The representative sample in the form of gas or liquid can be extracted to assess indirect corrosion-related parameters, and those that assess direct-related parameters come most of the times as part of the system of interest itself. For the former two to be representative, they must be sometimes kept in conditions similar to those when under operation (i.e. operating conditions in terms of e.g. pressure and temperature) [31].

[A2] : Contact Environment Corrosion can virtually happen in any environment [20], namely gas, liquid or solid. Corrosion can also happen in mixed environments where the corroded part of the system of interest is simultaneously exposed to alternating phases. In this case, the state of matter (i.e. gas, liquid or solid) responsible for the most significant corrosion rate is to be considered during the selection process. Note that the environment, which is characterized by a given state of matter, is dependable on the conditions under which the system of interest is operating.

[A21] : Gaseous Environment Numerous gas compounds can be responsible for corrosion. To find a structure during the selection process, the attribute [A21] is subdivided into two sub-attributes: (1) Oxygen-free environment; and (2) oxygen-bearing environment. Further sub-attributes following [A21] and [A22], from a corrosion monitoring point of view, are shown in figure 4.5:

FIGURE 4.5: Selection process categorization [A21]

[A22] : Liquid Environment One way to classify a liquid is by its water-content. Liquids that contain water as solvent are called aqueous solutions whereas those that do not are called non-aqueous solutions. As for aqueous solutions, they can be further categorized into natural and synthetic. From

a corrosion monitoring point of view, this type of distinction is relevant [31]. Figure 4.6 depicts the way [A22] is overly categorized.

FIGURE 4.6: Selection process categorization [A22]

[A23] : Solid Environment Corrosion monitoring is possible in a solid environment when the corroding part of the system of interest is exposed to e.g. soil and concrete. Other solid environments such as two metals that are in physical contact may lead to e.g. galvanic corrosion [C321] (*sect. (4.2.4)*). Monitoring this kind of corrosion mechanism is also possible [30, 31, 32], if the decision logic path leading to techniques from category [T] such as [T015] ; [T051] and [T06] (*sect. 4.2.1*) are conform.

FIGURE 4.7: Selection process categorization [A23]

[A3]: Material Properties Metals that are found in nature in their metallic state (e.g. Au, Ag and Pt) are less susceptible to corrode. Only metals that have been chemically treated (e.g. Fe-based alloys) corrode because of

the inherently unstable environment [26]. From the corrosion monitoring point of view, implications can be anticipated as many corrosion monitoring techniques (*sect.* 4.2.1) depend on corrodible metals' properties such as magnetism [A3111]. The categorization is constructed according to the structure shown in figure 4.8. Additional material properties that are relevant for certain corrosion monitoring techniques is the materials' morphology [39] (*fig.* 4.9).

FIGURE 4.8: Selection process categorization [A31]

FIGURE 4.9: Selection process categorization [A32]

4.2.3 Category [B] : Attributes related to the supposedly selected corrosion monitoring strategy

In practice, it is important to understand the features of the system of interest (*sect.* 4.2.2) and how it interacts with its surroundings. Any monitoring program requires sensors that must be installed or applied from reasonable distances and have to cope with the conditions under which the system of interest is operating, that is, in terms of e.g. background noise [B11], debris-bearing [B12], cleanliness [B13] and gradients of physical entities [B14]. Furthermore, attributes such as human safety [B15], and operating conditions [B21 to B25] also depend on the features of the supposedly selected corrosion monitoring strategy. Since these attributes depend on the supposedly selected techniques' ability to perform as designed, additional attributes are added to this category in order to assess the techniques' ability

to perform as desired, i.e. in terms of diagnostic- and prognostic capabilities [B3] and the techniques' speed of response [B4].

[B1]: Background Environment The environment in-which the system of interest is placed, in terms of e.g. noise and human safety, plays an essential role in selecting the most suitable corrosion monitoring strategy.

[B11] : Background Noise The noise present in the background, when non-filterable, plays a crucial role in determining what monitoring technologies are more likely to perform adequately. Some techniques are more resilient to such external factors than other. From a corrosion monitoring point of view, these external factors can be categorized as (fig. 4.10): [B111] thermal noise, [B112] electromagnetic noise (e.g. electromagnetic waves), [B113] mechanical noise (e.g. vibroacoustic waves and mechanical pulses), [B114] radioactive noise, [B115] chemical noise (e.g. pH fluctuations) [31, 32].

FIGURE 4.10: Selection process categorization [B11]

[B12] : Debris-bearing A form of corrosion (e.g. corrosion-erosion [C325]) can be induced by a debris-carrying process. The fluid carrying these debris might be in particular relevant for certain corrosion monitoring techniques (e.g. Fluid detection [T222]).

[B13] : Cleanability A non-clean system of interest is considered such when the supposedly selected technique cannot perform its function due to this particular detail. Coatings [C11] (sect. 4.2.4) and deposits such as debris, powder, grease and fungus might hinder the technique's supposed performance. Cleaning activities can be performed either manually or by pigging systems.

[B15] : Human Safety Emplacements where the system of interest can be accessed safely are not in need of robotized systems. Certain techniques can be robotized for a number of reason, including for safety [42].

FIGURE 4.11: Selection process categorization [B12], [B13], [B15]

[B14] : Gradient Within the boundaries of the system of interest, differences in physical quantities are observed: thermal [B141], pressure [B142], voltage [B143], height [B144] (e.g. the ability to sustain the same eye-level during the monitoring process) and velocity [B145].

FIGURE 4.12: Selection process categorization [B14]

[B2] : Physical Limitations These limitations are set based upon the limitations that technology has overcome. The degree to which these limitations can be surmounted are in certain cases purely commercial which adds a whole other dimension in performing the selection process. Therefore, commercial aspects with this regard are not considered during the selection process - for example, the characteristics of a given probe can differ from commercial brand to another, in terms of e.g. materials used, size and sensitivity.

Corrosion monitoring technologies can physically be limited due to a number of factors, including [B121] temperature limitations, [B122] pressure limitations, [B123] geometrical limitations, [B124] chemical limitations, and [B125] biological limitations. These sub-categories are shown in figure 4.13.

FIGURE 4.13: Selection process categorization [B2]

[B21] : Temperature Limitations The ability for a corrosion monitoring technique to sustain a certain degree of temperature is technologically limited. During the selection process, the limitations are set, from a corrosion monitoring point of view, according to the following:

- [B211] from 0°C to 50°C
- [B212] from 50°C to 300°C
- [B213] from 300°C to 600°C
- [B214] from 0°C to -20°C

[B22]: Pressure Limitations The ability for a corrosion monitoring technique to sustain a certain degree of pressure is technologically limited. During the selection process, the limitations are set, from a corrosion monitoring point of view, according to the following:

- [B221] around 1 *bar*
- [B222] up to 30 *bar*
- [B223] up to 100 *bar*
- [B224] less than 0.5 *bar*

[B23] : Geometrical Limitations The geometry plays an essential role in determining what monitoring program suits the system of interest the best [31]. This can be seen from two angles: the topology [B231] and the dimension [B232]. The former filters out corrosion monitoring techniques that do not fit the system of interest in terms of shape and architecture, whereas the latter deals more with how the corrosion monitoring technique fits into the system of interest.

[B24] : Chemical Limitations Many corrosion monitoring techniques, in particular electrochemical techniques, have limitations related to the

chemistry of the monitored environment [31] such as transient chemical reactions that have not reached their steady-state [B241] yet, and temperature- [B244] and pressure induced reactions [B245] when corrosion is significantly stimulated by temperature and pressure, respectively. Other corrosion techniques are driven by reduction-oxidation (redox) reactions [B242], among these redox-driven techniques are techniques that are easily hindered by secondary chemical reactions [B243] and influence the exchange of electrons [32].

[B25] : Biological Limitations Corrosion monitoring in microbial environments may lead to corrosion in the form of e.g. pitting as in many cases corrosion damage cannot be contributed only to chemical effects [B24]. The circumstances under which microbiological-influenced corrosion (MIC) [C326] can develop depend on the microbiological activities within the the boundaries of the system of interest [15]. The selection process considers such decision logic path only if the failure analysis prove the potential of such harmful effects.

[B3] : Diagnostic- & Prognostic Capabilities Depending on what is desired from the monitoring program, corrosion monitoring techniques are filtered out during the selection process based upon their individual diagnostic- and prognostic capabilities: (1) detect a corrosion occurrence within the system of interest; (2) localize it [B32]; then (3) measure [B33] and (4) predict [B34] its rate and evolution.

FIGURE 4.14: Selection process categorization [B3]

[B4] : Speed of Response The choices made in [B3] requires a coherent speed of response [B4] that optimally suits the wanted monitoring program. Depending on how the failure analysis evaluate the corrosion rate, an appropriate speed of response needs to assigned. As for the commercial aspects of this particular attribute (e.g. sensitivity), variation can be found from brand to brand when considering corrosion monitoring techniques of the same nature. These aspects are once again being discarded and only technological feasible solutions are treated in this selection process.

FIGURE 4.15: Selection process categorization [B4]

4.2.4 Category [C] : Attributes related to the underlying corrosion mechanism

In addition to comprehending the practical concerns related to the system of interest (category [A]) (*sect. 4.2.2*), and those that are related to the supposedly selected monitoring strategy (category [B]) (*sect. 4.2.3*) - it is important to filter out corrosion techniques based on attributes that are related to the underlying corrosion mechanism, its occurrence, and the techniques used in order to prevent/mitigate such occurrence. Figure 4.16 depicts the (sub-)attributes that contribute to the selection process.

FIGURE 4.16: Selection process categorization [C]

[C1] : Corrosion Inhibition Certain corrosion inhibition techniques, such as coatings [C11] and corrosion insulation [C12], limit a number of corrosion techniques of accessing the system of interest whereas other inhibition techniques, such as cathodic protection [C13] and chemical inhibitors [C14], provide promising opportunities to proactively assess the condition of the system of interest.

[C2] : Corrosion Occurrence Corrosion monitoring techniques are designed to perform one or more of the capabilities mentioned in [B3] (sect. 4.2.3), and also depending on where the corrosion mechanism took place. However, performing these capabilities successfully depend on where the corrosion mechanism is developing. In fact, corrosion can occur on the surface [C21] or in the sub-surface [C22]. When placed outside the boundaries of the system of interest, the on-surface [C21] occurrence of corrosion can be either internal [C211] or external [C212].

[C3] : Corrosion Mechanism Generally, corrosion includes two main forms of mechanisms, that is, general- [C31] and localized corrosion [C32]. The latter form of corrosion includes further phenomena such as pitting [C322], crevice [C323] and stress corrosion cracking [C324] [9], and finally erosion corrosion [C325]. Other mechanisms such as MIC [C326] may lead to

corrosion mechanisms previously mentioned e.g. pitting. However, in the present review, the distinction is made between e.g. pitting and MIC because of its relevance from a corrosion monitoring point of view. Identifying the root cause of certain corrosion mechanisms is central for assigning an appropriate monitoring strategy.

4.3 Wear Monitoring

Wear monitoring refers to (continuous) measurements of degradation caused by wear and performed under industrial or practical operating conditions. The assessing of wear-induced parameters is a complex practice because of the diversity of applications and the laws of motion that are inherently involved. Similar to corrosion monitoring, in order to obtain a synergistic CM strategy, it is important to comprehend the attributes related to the three categories [A], [B] and [C].

In principle, categories [A] and [B] remain the same as for corrosion monitoring with an adjustment on the *contact environment* category [A2]. The present selection method considers a wear mechanism occurring only in solid environments [A23]. A wear mechanism, such as erosion, occurring in a [A21] gaseous and/or liquid [A22] environments fall under the failure mechanism [C325] previously treated.

Additional attributes are also added to the selection matrix (*app. B*) e.g. tribology [A4] and motion [A5]. Finally, the condition monitoring techniques in category [T] have been adjusted to category [C], hence its categorical change.

4.3.1 Category [T]: Wear Monitoring Techniques

A summary of existing wear monitoring technologies [2] are clustered in figure 4.17.

FIGURE 4.17: Condition Monitoring Techniques for Wear [T]

Vibration Analysis A vibration signature is associated to a certain machine in standard condition. Fault development changes that signature in a way that can be related to the fault. The term "*mechanical signature analysis*" is also given to vibration analysis [10]. This excludes terms such as "*electrical signature analysis*" from being confused with the more generic term, that is, *dynamic monitoring* [2]. Electrical signature analysis is not included in the present design project.

The processing techniques for vibration analysis can be further clustered into four main domains, namely, the time domain, the frequency domain, the time-frequency domain and the modal domain. The time-domain processing techniques are listed in figure 4.18.

FIGURE 4.18: Processing Techniques for Vibration Analysis in the time domain [T3]

Furthermore, the remaining domains are depicted as :

FIGURE 4.19: Processing Techniques for Vibration Analysis in the frequency- [T4], the time-frequency- [T5] and the modal domains [T6]

4.3.2 Category [A] : Attributes related to the system of interest

[A4] : Tribology When applicable, the selection process for wear can be based on the following three aspects [2]:

- the lubricant condition [A41],
- machine wear [A42],
- contaminants [A43].

Further selection attributes (*fig. 4.20*) can be adopted for the lubricant's nature [A41], i.e. oil [A411] or grease [A412] [23] and on the contaminants' nature, i.e. fluid- [A431] or particle-like [A432] [2].

FIGURE 4.20: Selection process categorization [A4]

[A5] : Motion The progressive loss of materials from contacting surfaces are subject to the laws of motion. Such phenomenon occurs when relative motions are involved along with the acting forces. The selection process depends on such motions and can be categorized into: the statics [A51], the kinematics [A52] and the dynamics [A53] of the system of interest.

[A51] : Statics The statics of the system of interest is concerned by analyzing, if applicable, stationary loads [A512] that do not experience acceleration [A511]. The notions of load and relative velocities are relevant for selecting a suitable wear monitoring strategy (*fig. 4.21*).

FIGURE 4.21: Selection process categorization [A51]

[A52] : Kinematics The kinematics of the system of interest is considered by taking into account the way its motion is sustained [A521] and the way it moves [A522]. In all this movement, the shaft is considered the body of reference resulting in a number of additional sub-attributes, namely, movements that are:

- shaft phase-locked [A5231],
- shaft phase-unlocked [A5232], or
- fluid flow-linked [A5233].

Motions that are shaft phase-locked [A5231] contain harmonic series, in the form of integers, that can be linked directly to the shaft's frequency. On the other hand, the harmonics related to motions that are shaft phase-unlocked [A5232] are not necessarily integers. Furthermore, motions that are not related at all to the shaft's frequency are considered fluid flow-linked motions [A5233].

The categorization of the kinematics-related attributes are as follows:

FIGURE 4.22: Selection process categorization [A52]

[A53] : Dynamics The dynamics is considered by analyzing, if applicable, the mechanical signals generated from the system of interest. The most fundamental categorization is performed according to the signal's stationarity as shown in figure 4.23.

FIGURE 4.23: Selection process categorization [A53]

Stationary signals [A532] contain statistical parameters that do not vary with time and can either be further categorized into deterministic- [A5321] and random signals [A5323]. On the other hand, non-stationary signals [A533] contain statistical parameters that do vary with time. Continuously varying signals [A531], transient signals [A532] and cyclo-stationary signals [A533] are considered within this classification.

There is no hard rule for distinguishing between these types of non-stationary signals, but in general continuously varying signals [A531] exist, in a theoretical sense, for an infinite length of time, as opposed to transient signal [A532] which exist for a brief length of time. Cyclo-stationary signals [A533] have statistical properties which vary periodically in time.

4.4 Assimilation phase

Chapter 3 outlined the project's design methodology which consisted of a design cycle within an engineering cycle (*fig. 4.24*). The selection matrices for corrosion (*app. A*) and wear (*app. B*) form the backbone and one of the most time-consuming steps in the project's design cycle, i.e. the design phase. Assimilating the selection matrices in a DSS requires a good understanding of what and how a typical decision support system (DSS) should perform.

FIGURE 4.24: Design- and engineering cycle

The present design project opted for a single design-candidate as a promising design solution, i.e. a DSS capable of suggesting choices based on a structured logic. These so-called suggestion systems that are able to mimic the reasoning process a human would use in reaching a decision is called a prescriptive-based suggestion system. In this case, the human expertise can be codified into a set of "if-then" rules and expert systems (ES) are often used to construct such a prescriptive process [43]. In the present design project, the DSS-candidate for the design solution is an ES.

An ES - also referred to as a knowledge-based system or a rule-based system - is a problem-solving computer program that achieves good performance in a specialized problem domain that is considered difficult and requires specialized knowledge and skill [16]. According to the *online Merriam-Webster Dictionary*, an ES is meant to mimic the reasoning of a human specialist.

A simple ES must be able to contain a certain number of features, namely: (1) to determine the system's main objective, i.e. selecting suitable CM-strategies (*sect. 1.2.2*) ; (2) to generalize the rules regardless the selected outcome (CM-strategy), meaning that the rules do not describe a specific situation ; and finally (3) to supply the facts or attributes, detailed in the first sections of the present chapter, to the ES and get answers in return.

These above-mentioned characteristics or features lead to the block diagram of an ES (*fig. 4.25*). Such a system consists, from an architectural point of view, of the following parts [43]: (1) the knowledge base ; (2) the

inference engine ; (3) the user interface ; (4) the work space ; and (5) the data base. Moreover, operating the ES from the outside is made possible by human beings, namely (1) the knowledge engineer ; (2) the domain expert ; and (3) the decision-maker.

FIGURE 4.25: Expert System Architecture

The knowledge base also known as *the rule base*, represents the problem-solving part of the factual knowledge found in the literature (sect. 4.2 and sect. 4.3). The selection matrices in appendix A and appendix B shape the knowledge base in its essence. This knowledge is expressed in the form of *if "some antecedent" - then "some consequence"*.

The inference engine tries to derive the *consequence* from the knowledge base by providing a methodology for *reasoning* and *formulating* the conclusions in the form of a suitable CM-strategy. When searching through the knowledge base, it matches the facts (or attributes) to the antecedents of the pre-established rule. If the rule matches, the immediate consequence can be executed. Several of the matching rules are chained and the sum of all the consequences leads to the formulation of the corresponding conclusion. In ES terminology, this conclusion is seen as a set of confidence variables and each confidence variable is represented by a CM technique. Two methods of this chain reasoning exist when using inference rules: (1) forward chaining and (2) backward chaining.

Forward Chaining : starts from the available data and tries to find satisfying rules. When a given number of rules is satisfied, the corresponding consequences are added to the knowledge base until all information from the data base is exhausted. This method is *fact-driven*.

The ES' inference engine starts with the available set of "if-then" rules that satisfy that particular outcome [T09] (fig. 4.26) and then tries to compare it with the decision-maker's input.

FIGURE 4.26: Forward Chaining

In this example, the two decision logic paths leading to [T09] contain attributes (e.g. [A11], [B242] and [C32]) from which the inference engines starts and tries to find satisfying rules provided by the decision-maker.

Backward Chaining : tries to prove a conclusion (or outcome) by confirming the satisfaction of all its corresponding "if-then" rules. This method is *goal-driven*.

The ES' inference engine starts with assuming all available outcomes (including the outcome [T09] in figure 4.27) and tries to trace back if the decision-maker provided input that is similar to the "if-then" rules stated in the corresponding logic block.

FIGURE 4.27: Backward Chaining

In this example, the outcome [T09] is selected as suitable CM technique until proven otherwise, that is, the inference engine assumes [T09] as a potential outcome. The outcome is selected only and only when the decision-maker provides the necessary set of attributes displayed in figure 4.27.

The attributes related to CM techniques are organized in categories. However, not all attributes are equally applicable to each individual CM

technique. This explains the presence of certain neutral elements in the selection matrices. Consequently, the inference engine tend to request values for the attributes in a random- and sometimes contradictory way. Backward chaining solves this issue by creating fictive confidence variables and hold the logic of the entire selection process intact. To filter the fictive confidence variables out, they are assigned a value of " $Conf = 0.0$ " whereas the remaining confidence variables, in the form of CM techniques, are assigned a value of " $Conf = 1.0$ ".

Figure 4.28 depicts the outcome of a given selection process without filtering out the fictive confidence variables ($Conf = 0.0$)

FIGURE 4.28: The ES-based DSS outcome before filtering the fictive confidence variables

The user interface enables the decision-maker to interact with the ES by requesting input, in the form of providing actual facts (or attributes), and sending back outputs in the form of questions about new facts (or attributes) or ultimately providing a conclusion (or CM-strategy).

The work space is a storage area where the ES keeps track of the facts it has been given thus far.

The data base an ES that is used for decision support often uses data bases [43]. It is meant to provide the user with facts that apply to a particular situation. For example, when the conclusion is a particular CM technique [T] - the data base can supply the decision-maker certain facts that apply to this particular CM technique, e.g. the PF-interval, the required skill level, the

CM's potential and limitations, in addition to other characteristics such as the possibility of continuous monitoring.

The ES human implication The FM- and CM experts along with the knowledge engineer contribute to the development of the ES. The (FM- and CM) experts contribute their expertise in the field and the knowledge engineer translates this expertise into a program compatible with the ES architecture. The end goal of such a collaboration is to solve the problem the decision-maker is facing, i.e. advise in a suitable CM-strategy.

The extensive number of (sub-)attributes leads to a combinatorial explosion of the "if-then" rules within the categories previously described. The complexity increases even more so as the number of CM techniques increases. This has a direct impact on how the DSS should be built, maintained and eventually upgraded. Therefore, such an ES complying with the requirements in table 2.2 is consequential for the successful implementation of the present design project.

4.5 ES-based DSS Integration in other CBM Guidelines

Several criteria have to be reviewed in order to determine whether a given system of interest is suitable for condition-based maintenance (CBM). A decision scheme has been developed for this particular purpose [22]. It requires answering a series of questions detailed in appendix E in order to evaluate the applicability of the CBM policy.

Validation of the Guidelines The decision scheme (fig. E.1) has been adapted to the design project at hand and puts an emphasis on question "A2: *Can these parameters be measured?*". The ES-based DSS treated in this context aims to provide guidance to this particular question (tab. 4.1).

TABLE 4.1: Guideline for CBM applicability for the system of interest

<i>A1: Possible to identify critical component, FM and associated condition parameters?</i>	
-	Critical component: system of interest FM: e.g. corrosion
<i>A2: Can these parameters be measured?</i>	
-	Parameters related to the system of interest: [facilitated by the DSS] Parameters related to the supposedly selected CM strategy: [facilitated by the DSS] Parameters related to the FM: [facilitated by the DSS]
<i>A3: Can measured quantities be translated into maintenance intervals/failures?</i>	
-	Depends on the supposedly selected CM strategy
<i>A4: Does applying CBM yield financial or safety benefits?</i>	
-	Erect a business case based on the DSS outcome
<i>A5: Possible to implement CBM in organization?</i>	
-	Depends on the decision-maker's motivation
<i>A6: Is commercial CBM available?</i>	
-	The DSS advises only in CM- and NDT techniques that are commercially available

Provided that question A1 is positively answered, the ES-based DSS can be launched to derive an answer from question A2. The answer to this question dictates how the remaining questions will be dealt with.

Chapter 5

Validation by Case-studies

The design cycle treated in chapter 3 consisted of an iteration of the problem investigation (e.g. stakeholders (*tab. 2.1*)), requirements (*tab. 2.2*)), the design solution i.e. the decision support system (DSS) (*chap. 4*), and the validation phase for corrosion monitoring which is detailed in the present chapter. This validation is based on three cases from the literature, and one case is documented based on an actual CM activity. The details from these cases are compared and incorporated into the ES-based DSS-prototype. The DSS-prototype is validated when the selection outcome corresponds to the CM technique used in these cases. When additional CM techniques are proposed, a discussion is made about forming CM strategies from the different combination of techniques that are advised by the DSS-prototype. This discussion is inspired by the proposition made in section 3.2.3 about the CM financial feasibility. As for wear, one observation is performed based on an actual case-study. The observation does not include any further details whatsoever regarding its validation.

FIGURE 5.1: Design- and engineering cycle

5.1 Validation based on literature case-studies

The literature-based case-studies serve as a testing tool for evaluating the DSS-prototype performance against the pre-established requirements. The case-studies are extracted from situations where inspection of poor quality is due to the lack of the proper material needed, resulting in high repair costs. According to the case-studies, performing condition-based maintenance (CBM) proved to be successful because of the right choice of the techniques. It is within this context that the DSS-prototype is tested and evaluated. The aim of the present section is to compare the DSS-prototype outcome to the chosen CM techniques based on the facts that are provided in these papers.

5.1.1 Corrosion monitoring using the field signature method inspection tool

The corrosion monitoring operation was conducted by the Canada-based Pangea Solution Inc. [27] and described the circumstances under which the field signature method (FSM) was used. Mitigating procedures such as injecting chemical inhibitors was believed to be difficult. However, according to the study, the FSM has led to early warnings which prevented further internal corrosion degradation and eventually, failure. The corrosion mechanism used to be pitting.

The program concerned a 168.3mm wide pipeline of 12km long transporting sour gas. Although the pipeline was underground, it was decided that unearthing was an option and therefore granted physical accessibility to the system of interest (i.e. pipeline).

FIGURE 5.2: Field signature method installation with protective cover

It was decided to proceed with FSM by measuring the pitting rate (from September, the 14th to November, the 19th) with a two-day measuring

interval. This resulted in detecting different amounts of wall-loss per monitored area.

The selection outcome provided by the DSS-prototype suggested six different corrosion monitoring techniques of which FSM is one.

- Pit Initiation Analysis (PIA)
- Field Signal Mapping (FSM)
- Thickness Measurement (TM)
- Remote Field Testing (RFT)
- Computed Tomography (CT)
- Strain Measurement - Fiber Optic (SM)

The FSM used in this case-study figures among the CM techniques suggested by the DSS-prototype. This means that the DSS-prototype's outcome corresponds to CM technique used in the case-study. In addition to FSM, the DSS-prototype suggests that, under these particular circumstances, other CM techniques could also be used. However, by referring to the selection matrix (*app. A*), only a limited number of CM strategies can be formed. In fact, pit initiation analysis (PIA) and thickness measurements (TM) have limited capabilities regarding real-time pitting detection, as opposed to strain measurements (SM) which has limitations with respect to measuring capabilities. On the one hand, suggesting PIA and TM is meant to enhance the potential CM strategy's capabilities in measuring the pitting rate, and on the other hand, suggesting SM is meant to enhance the detecting capabilities. As a consequence, the decision-maker's basic options to form a technologically feasible CM strategy should be based on either (1) one of the various combinations composed of FSM, remote field testing (RFT) and/or computed tomography (CT), or (2) combining PIA or TM with SM in another scenario. Once a binding scenario is selected, the techniques of the other scenario remain optional, depending on how crucial detecting and/or measuring the pitting mechanism would be.

Within this context, Pangea Solution Inc. selected FSM which is able to both detect and measure the pitting mechanism. According to the DSS-prototype, Pangea Solution Inc. could also have selected RFT, CT, or even combining SM with PIA or TM. If in the present case, Pangea Solution Inc. decided, for example, to enhance the detecting capabilities of FSM, SM could be a viable asset to form a more suitable CM strategy. Note that analyzing the economic benefits of the various combinations could add an additional dimension in the decision-making process.

5.1.2 Acoustic Emission for Corrosion Detection

The paper described the use of acoustic emission (AE) for corrosion detection [3]. The system of interest concerned a storage tank (*fig. 5.3*) made of carbon steel in low noise environments. The costs of removing such a tank from service and cleaning it from the inside were considered to be too high.

FIGURE 5.3: Corrosion activity occurring in a straight geometry (tank's floor)

During this case-study, AE was used for detecting corrosion and quantifying the rate at which corrosion cracks propagate. Moreover, it was intended to accurately localize such cracks by triangulation, especially when other sources of cracks might be present, e.g. corrosion cracks of tank shells under insulation.

Additional attributes, which were not explicitly mentioned in this paper, inherent to a typical storage tanks were assumed during the selection process e.g. contact environment and pressure gradient. The outcome of the selection process is AE. Two Additional corrosion monitoring techniques have been issued from the same DSS' selection process:

- Acoustic Emission (AE)
- Field Signal Mapping (FSM)
- Guided Wave Testing (GWT)

The DSS-prototype suggested AE as described in the paper. The DSS-prototype also suggested other CM techniques demonstrating the fact that the storage tank, under these particular circumstances, could be monitored with other techniques than AE, namely FSM and GWT. However, according to the selection matrix (*app. A*), depending on GWT alone would not be feasible under the present facts provided by the decision-maker. In fact, GWT is not able to quantify the rate at which cracks propagate. Therefore, GWT could be added to the selected CM strategy only to enhance its ability for detecting and localizing such cracks.

5.1.3 Corrosion Monitoring in Marine Environment in Croatia

The paper discussed the advantages of monitoring reinforced concrete in a renovated marine environment [12]. During this case study, the corrosion monitoring of reinforced concrete elements (in the form of beams and T-girders) started with the galvanostatic pulse (GSP) technique instead of e.g. visual inspection and chemical testing (in the form of pH-measurements and measuring sulfur and chloride content). Given the harsh atmospheric environment (i.e. ambient temperature and ambient pressure), migrating corrosion inhibitors have been applied to the surface in order to protect the reinforced steel within the concrete.

FIGURE 5.4: columns with corrosion damage

The newly implemented corrosion monitoring technique GSP was supposed to measure the corrosion rate and estimate the service life based on the measured values. According to table 5.1, as presented in the paper, the corrosion damage on the reinforcement cross-section has a non-linear growth.

corrosion current I_{corr} [$\mu A.cm^{-2}$]	corrosion damage
$I_{corr} < 0.5$	no corrosion damage expected
$0.5 < I_{corr} < 2.7$	corrosion damage possible in 10 to 15 years
$2.7 < I_{corr} < 27$	corrosion damage expected in 2 to 10 years
$27 < I_{corr}$	corrosion damage expected in 2 year or less

TABLE 5.1: Non-linear corrosion growth

Additional attributes inherent to a typical reinforced concrete were assumed during the selection process e.g. material morphology (i.e. the reinforcing elements suffering from corrosion are rough) and altitude gradient. These assumptions were due to the incompleteness of the information provided by the paper in question. The outcome of the selection process under these circumstances is electrodynamic polarization (EP)

and galvanodynamic polarization (similar to GSP) falls into this category. Additional corrosion monitoring techniques have been issued from the same DSS' selection process and are as follows:

- EP- Potentio-/Galvano-dynamic Polarization
- Acoustic Emission (AE)
- pH-Measurement

The DSS-prototype suggested the EP as suitable CM technique. Two additional CM techniques were suggested, namely AE and pH-measurement. Within this context, the pH-measurements can be used in combination with GSP or AE in order to better support the service life predictability of the reinforced concrete.

However, during the DSS' selection process, it was assumed that a specimen could not be extracted from the system of interest. In the scenario where this is desirable, additional techniques were proposed and the DSS' selection process issued the following (in addition to GSP, AE and pH-measurements):

- Chemical Analysis (CA) - Sulfur Content
- Chemical Analysis (CA) - Chloride Content

It is worth mentioning that the CA techniques measuring the contents of sulfur and chloride used to be employed before implementing the GSP in order to assess the structure's damage. Nonetheless, according to the paper, the additional assigned techniques alone were not suitable for monitoring when considering the decision-maker's desire, i.e. measuring and predicting the corrosion damage.

In all three literature-based case-studies, the DSS-prototype suggested the CM techniques that were used to monitor the corrosion in each respective case. Moreover, the DSS-prototype provided also other CM techniques that could be used in order evaluate various CM strategies. However, the consequences of having additional techniques could result in one of the following scenarios:

1. the DSS-prototype is not selective enough, or
2. the situation described in the papers results in more than one feasible CM technique.

Referring to the selection matrix suggests a combination of both scenarios. The first scenario arises from the fact that some CM techniques could not be used individually, but in combination with an other technique to meet the decision-maker's desires. The second scenarios is due to the fact that certain CM technique could be used independently from the other techniques,

unless enhancing the monitoring capabilities (e.g. increase the detectability and the measurability) is desired. Either case, deciding which of the selection outcomes belong to which scenario is not conclusive. The respective cases do not include information about the technological feasibility of all the CM techniques issued from the selection process.

5.2 Validation based on a documented case-study

The corrosion monitoring operation was documented in order to compare the DSS-prototype's outcome with the corrosion monitoring technique actually used in the field, namely the Remote Field Testing (RFT) technique in combination with the Pit Initiation Analysis (PIA). The interviewee was a lead engineer responsible for maintaining a local gas station owned by the National Iranian Gas Company (NIGC). To validate the case, the selection process went through the three categories [A], [B] and [C].

Category [A] The system of interest concerned pipelines transporting natural gas in the form of pressurized methane CH_4 . The quality of the transported gas was considered sour, and moist during winter. The pipelines themselves were made of stainless steel and used to have a rough surface.

Category [B] The background noise surrounding the system of interest were all considered to be filterable except for the vibrations caused by the dynamic pressure in play. Moreover, differences in temperature, especially during winter, and pressure were usual for pipelines operating in such an environment. Furthermore, the downstream consumption of the natural gas caused differences in the flow velocity of the transported gas. Additional elements were also present in the background, such as the debris formed because of the high sulfur content. However, the pipelines were considered to be safe and cleanable by the use of pigging cleaning systems.

The monitored cross-sectional parts of the pipelines were considered straight. Meanwhile, it was known that the corrosion activities were fueled by oxidation-reduction reactions and no microbiological activities were observed. Furthermore, the NIGC was interested in detecting, localizing and measuring these corrosion activities.

Category [C] The corrosion mechanism occurred internally in the form of pitting. The NIGC opted for cathodic protection in order to mitigate these corrosion effects.

The DSS-prototype suggested four different corrosion monitoring techniques, of which RFT is one. The details of the selection process are found in appendix D.

- Pit Initiation Analysis (PIA)

- Field Signal Mapping (FSM)
- Remote Field Testing (RFT)
- pH-Measurement

Referring to the selection outcome, the DSS-prototype has been validated for this case. Even more so, the DSS-prototype suggested additional techniques that might enhance and/or replace the actual corrosion monitoring strategy opted for, in terms of e.g. increasing the detectability and the measurability of the corrosion monitoring strategy.

However, NGIC also opted for piggable Ultrasonic Testing (UT) techniques. Yet these techniques were not part of the selection outcome. This is due to the fact that the DSS-prototype does not consider techniques that are compatible with piggable systems, nor does it consider the dependency between the selected attributes. During the present case, such dependency occurred between the attribute for roughness and the attribute for cleanability. The system of interest would not have been considered "rough" if an internal cleaning operation took place (which in the actual case did). The fact that the attribute for roughness has been selected, eliminated all the techniques that do not deal with rough surfaces, including the UT techniques.

Linking the (sub)attributes within and between the categories [A], [B] and [C] would have solved the problem related to the UT techniques which were not part of the selection outcome. A redesign involves linking the (sub)attributes within the logic blocs of the ES-based DSS in such a manner that all dependent these (sub)attributes will interact accordingly (e.g. attribute for roughness interacting with the attribute for cleanability).

5.3 Observation based on a conducted case-study

The case study provided by Gasunie, via DNV-GL, concerned ball valves in the high-pressure gas transportation network. Generally, these underground valves are usually in the open position and are only occasionally closed. They are designed to isolate certain sections of the pipeline from others when needed, e.g. in the case of an emergency or during maintenance. During these occasional events (once per 2-3 years), the need for a given (ball) valve to fulfill its one and only function is crucial. Any failure of the valve whatsoever will inevitably lead to serious consequences (e.g. potential endangerment of both the environment and the maintenance personnel). In practice, such failures do occur and nowadays occur even more frequently due to the ageing factors, increasing even more the likelihood of risks resulting from a non-functioning valve. As the average age of the valves increases, the failure rate at which a (ball) valve fails tend to follow a stochastic behavior. As a result, uncertainties must be taken into account

when dealing with incipient failures, rendering the time-based maintenance policy completely ineffective. However, The inherent presence of such uncertainties creates a fertile ground for an alternative maintenance policy, termed *the condition-based maintenance policy*.

The absence of a structured history of failures lead Gasunie, in collaboration with DNV-GL, to investigate free texts accumulated over the years (since the 1990's). Text mining techniques were employed in order to retrieve qualitative data. According to the literature, sealing mechanisms are at risk of numerous pressure-induced failures [19, 36, 46], e.g. compression and (rapid gas) decompression, stress relaxation, extrusion and nibbling, volume change, erosion as well as other damage caused by wear and fatigue (hammer effect). The forces generated by these pressure-related phenomena must be absorbed by the inner parts of the ball valve itself. Moreover, the transported fluid can cause corrosion, erosion and degradation of soft seals and wear on seal surfaces. It can, under certain conditions, also cause cavitation on the metal surfaces. As for corrosion, the inner parts of the ball valve are more determined by the quality of the transported gas. The quality is assumed to be high, rendering the metallic inner parts less susceptible to corrosion. However, the wear mechanism does occur every now and this then leads to the degradation of seals. Additionally, erosion that is due to sand and "black powder" can also lead to debris deposits on the seals, but do not often occur [41].

In addition to the previously mentioned failures, temperature- and chemical- induced failures might also be detected [19]. However, such failures are assumed to be negligible for the ball valve under study. The ball valve operates in relatively moderate temperatures and the occasional exposure to pressure peaks, ultimately leading to local increases in temperature, are assumed negligible. Similarly, degradation due to chemical reactions is outside the scope of the present study. On the basis of these assumptions, pressure-induced failure mechanisms, in the form of wear, are considered most relevant for the present case-study.

Comparing and then incorporating the (sub)attributes lead the developed selection methodology to the following CM strategy:

- Strain Measurement (SM)
- Elastomer Compatibility Test (ECT)

According to the selection matrix in appendix B, the wear monitoring strategy SM and ECT is capable of detecting and predicting wear occurrences. Measuring strains by SM could reveal changes in the geometry of the system of interest whereas the ECT could be engaged in predicting any wear occurrence. However, predicting wear based on ECT requires an accelerated life testing which itself requires statistical data. Nonetheless, the technological feasibility of this observation cannot be validated, as the nature of this observation suggests.

Chapter 6

The Design Project Deliverable

The DSS-prototype, as described previously in chapter 5, is an (initial) approach on how to advise in suitable CM-strategies in terms of functionality. During the present design project, the DSS-prototype is supposed to be validated over and over again within the design cycle until it becomes a validated prototype. This results in having a solid idea about the DSS-prototype's functionality and construction. Moreover, it helps evaluating the prototype's techno-economic realizability and the impacts it may have on its context (or environment) (*fig. 3.5*). The present chapter provides a critical discussion on the design project as a deliverable.

6.1 Requirement review of the DSS-prototype's Functionality and Construction

The DSS' functionality concerns the extent to which the requirements (*tab. 2.2*) are met. This results in identifying not only what the actual DSS-prototype can perform in its direct environment (i.e. DSS-prototype functionality), but also how the DSS-prototype performances are carried out (i.e. DSS-prototype's construction).

General Requirements & Applicability The functionality of the DSS-prototype itself is quite straightforward. Once engaged in the selection process, the decision-maker supplies the ES-based DSS-prototype with facts (inputs) according to one's understanding (*req. StR1*). Based on the provided facts (or attributes), the DSS-prototype continues to supply the decision-maker with further elements until the selection process is terminated (*req. StR2 and StR18*). However, providing the DSS-prototype with actual facts requires a thorough understanding of the system of interest, its environment and the underlying failure mechanism (FM) (*req. StR4 and StR6*). Moreover, the system of interest has to be selected based on the pre-established criticality analysis (*req. StR3 ; StR5 and req. StR7 to StR9*). In brief, five steps, which are depicted in figure 6.1, are to be accounted for during a successful selection process. The selection method, developed in the present design project, is performed in step 3.

FIGURE 6.1: DSS' hierarchical structuring

CM Financial- & Technological Feasibility Requirements Although a mechanism-based failure analysis (*step 2*) can be extensive, the decision-maker should put an emphasis on the elements that might be encountered during the selection process (*step 3*) and therefore anticipate the DSS-prototype wanted input. These elements are related to the main attributes detailed in *chapter 4*, namely, (1) the features of the system of interest ; (2) the medium in-which the system of interest is placed ; and (3) the underlying FM. Once the selection process completed, the eventual CM-technique(s) output¹ (*req. StR14 to StR17*) facilitates the decision-maker's ability to erect a business case (*step 4*), and hence paving the road for a suitable CM-strategy selection (*step 5*) (*req. StR10 to StR12*).

Ease-of-Use Requirements The decision-maker is involved in all five steps of the DSS' hierarchical structuring (*fig. 6.1*) and is considered to be one of the most important stakeholders. Meanwhile, his interaction with the DSS - in particular the selection process (*step 3*) - is granted by the ES' user interface (*req. StR21 and StR22*). Moreover, the ES used in the present design project grants both the knowledge engineer and the CM-expert the possibility of upgrading and/or maintaining the selection process through a backdoor (*req. StR19*), if an eventual re-construction is required. However, such maintenance operation is only accessible if the stakeholders are UT-related (the maintenance operators in the Alexander's list - *tab. 2.1*).

¹all CM-techniques detailed in chapter 4 are both technologically mature and commercially available

Reusability Requirements The ES-based DSS provides access to decision-makers willing to perform CBM regardless the application, as long as the applicability requirements are met (*req. StR7 to StR9*). Within this context, scales thinking (*sect. 3.1*) is used to anticipate the way such scalability would be granted (*req. StR23*). In practice, however, uploading the files into the server at the eleventh hour made fulfilling this particular requirement somehow troublesome.

Requirements Checklist is made based on the clustered categories in table 2.2.

- General Requirements & Applicability
  - ✓ General category (*req. StR1 to StR6*)
  - ✓ Applicability category (*req. StR7 to StR9*)
- CM Financial- & Technological Feasibility Requirements
  - ✓ Financial feasibility category (*req. StR10 to StR12*)
  - ✓ Technological feasibility category (*req. StR14 to StR18*)
- Ease-of-Use Requirements
  - ✓ Maintainability category (*req. StR19*)
  - ✓ Readability category (*req. StR21 and StR22*)
- Reusability Requirements
  - ✗ Scalability category (*req. StR23*)

6.2 The DSS-prototype Techno-economic Realizability

The resulting truth that the DSS-prototype is technically realizable is discussed in chapter 5. Based on the requirements met, the first step is to have the DSS-prototype's functionality in section 6.1 approved. The degree of the requirements' satisfaction dictates to what extent the DSS-prototype is realizable. Such realizability concerns the certainty that it is both technically and economically worthy to produce the ES-based DSS. This means that implementing the prototype after being developed, tested and validated requires more than just a technical evaluation. The economic benefits of such a prototype should also be justified.

"Time is money says the proverb, but turn it around and you get a precious truth. Money is time²"

---

²said George Gissing

The economic benefit of such a DSS can be justified by the few minutes it takes to go through the whole selection process (in dynamic thinking section 3.1). The alternative approach is to dedicate the necessary resources in order to achieve the same result. Assuming that both approaches deliver the same reliable outcome, the means for choosing the alternative approach would not only be more time-consuming, but also more costly especially when a third party is involved. In this case, the end does not simply justify the means because of the disproportions in the respective costs.

To avoid additional costs, the ES used to develop the DSS-prototype fulfills the requirement StR23 for scalability. It is possible to produce the selection method by installing a licence-free server at the desired location. This leaves the UT-related stakeholders (the license-owner) responsible for accessing, maintaining and upgrading the ES' logic blocks.

6.3 The DSS-prototype Socio-technical Impact

The stakeholders in the Alexander list (*tab. 2.1*) are mainly influenced by the knowledge needed to successfully carry out the design project. The transferred knowledge was then used to affect the remaining stakeholders (e.g. case-study providers). To assess the DSS-prototype socio-technical impacts, the stakeholder-domain must be extended to a macro-stakeholder domain where external parties are to be considered as well e.g. the government and law makers including ISO-experts. This socio-technical system deals with a wide range of additional elements shown in figure 6.2

FIGURE 6.2: Socio-technical environment

As the parties from the stakeholder-domain interact more directly with the DSS and its design process, the parties from the macro-stakeholder domain interfere on one of the latest stages during the engineering cycle, namely the design evaluation (*sect. 3.2.3*). This is to say when the DSS advises in (a) certain CM technique(s), the outcome should comply with the regulations and the ISO-norms agreed upon. For instance, the selected CM strategy should adhere to a certain degree to the technological maturity

independently from the needed costs, especially when the failure of the system of interest might lead to catastrophic events. To anticipate these concerns, the macro-stakeholder domain is central for the socio-technical environment.

The DSS' (socio-technical) risk management The SWOT³ elements provide the chance to discuss the design project's internal factors, namely the *strengths* and *weaknesses*: the former to open new *opportunities*, the latter to convert, if possible, into additional *strengths*. Meanwhile, the DSS is better off when the remaining factor *threats* is neutralized. To achieve this, risk thinking is applied in consultation with the stakeholders. This risk thinking is used to anticipate appropriate countermeasures such that the corresponding components could be: (a) avoided ; (b) contained ; (c) taken ; or (d) delegated. A SWOT table has been drafted (*tab. 6.1*) for this purpose. The right half elements of the SWOT table are linked with the countermeasures used in risk thinking, i.e. (a), (b), (c), and (d).

TABLE 6.1: The DSS' SWOT elements

Strengths	Weakness
DSS is exclusive to a particular FM	(a) DSS is not universal
DSS has a structured selection methodology	(b ₁) -
Easy to maintain the logic blocks	(b ₂) Maintaining the DSS might be tedious
-	(c) -
No operating costs once implemented	(d) No guarantee for CM economical benefits
Opportunities	Threats
Easy to include as much expertise as desirable	(a) Coordination between multiple experts (e.g. CM- and FM- experts) is required
DSS can be used as a second opinion (an expert opinion)	(a) High costs associated with involving experts from different backgrounds
DSS provides an objective outcome	(b ₁) CM technologies are not always applicable
DSS enables CBM by further investments	(b ₁) Organizational conservatism
Easy to expand and upgrade	(c) -
First of its kind	(c) no benchmarking
-	(d) -

³SWOT : Strengths, Weaknesses, Opportunities, Threats

(a_i) **Avoiding the risk** The DSS' design process is time-consuming and is limited to two years. The knowledge needed for constructing a universal DSS including all FM is even more time-consuming. To avoid the risk associated with the lack of time, the stakeholders decided to scope the design project's objective to two FM, namely, corrosion and wear. Consequently, time was saved and invested to prove the DSS' technical realizability for e.g. corrosion monitoring. In the end, the choice made for building the DSS was based on an ES which considered such intentions for future extensions (i.e. to extend the DSS to remaining FM). Meanwhile, the threats related to the increasing number of experts from different backgrounds were exposed, in terms of communication and associated costs.

(b_i) **Containing the risk** For example, (b_1) the structured selection methodology results in providing the decision-maker consistent CM technologies, even though sometimes none of the CM technologies might be applicable. However, if such non-applicability persists, organizations tend to distance themselves from CBM and thus the DSS that advises in CM technologies, required to enable this particular maintenance policy, would be overlooked. As result, organizational conservatism towards the traditional way in performing maintenance is regarded as a threat for the present design project. To neutralize (or at least, to mitigate) such a threat, events were organized, in collaboration with the stakeholders, to make the industrial community more aware of the benefits the CBM policy represents, and thus provide the opportunity to invest more in CBM.

In an other context, converting *weaknesses* into *strengths* requires a proper risk handling, e.g. although (b_2) maintaining the DSS might be in certain cases quite tedious. Constructing isolated logic blocks mitigates this risk (risk handling by containing) and might even expose the corresponding *strength* to a new opportunity, i.e. the possibility of upgrading the logic blocks with additional "if-then" rules.

(c_i) **Taking the risk** Selecting appropriate CM technologies is nowadays intuition-based in the industrial community. Developing a structured DSS for CM technologies without the ability to compare its performances with similar selection methodologies exposes an additional challenge (from a benchmarking point of view). However, this creates the opportunity of implementing a DSS first of its kind.

(d_i) **Delegating the risk** Furthermore, (d) the risks associated to the economical benefits of the DSS' outcome has been delegated to the decision-maker (risk handling by delegating). This means that the DSS facilitates the elements needed for erecting an appropriate business case to evaluate the CM's economical benefits.

Chapter 7

Conclusion & Recommendations

A decision support system (DSS) for condition monitoring (CM) technologies promotes the pretext in which condition-based maintenance (CBM) is sometimes placed. In this work, enabling CBM from a decision point of view is made achievable. The first section (*sect. 7.1*) of the present chapter outlines the results issued from this work which resulted in a number of key conclusions. These conclusions were drawn from solving the design problem in question. The second section (*sect. 7.2*) gives an overview of potential directions in which future work could be beneficial.

7.1 Conclusions

The aim of the present design project was to provide a solution (which came in the form of the ES-based DSS) to the design problem: *"design a selection method able to advise in suitable CM strategies!"*. While providing the solution for the design problem, the following set of conclusions are drawn:

- The outcome of the present design project is both technically and economically realizable, meaning that the DSS-prototype could be implemented, and thus transferring the actual iterations within the design cycle into the engineering cycle.

Furthermore, the DSS-prototype has been designed according to the standards of the design cycle described in chapter 3. It has been developed, tested and validated under a certain number of constraints. The last iteration made, within the design cycle, introduced the following set of conclusions:

- The requirements on the stakeholder level have been facilitated/fulfilled. One exception is the requirement StR23 for scalability. However, the ES used in developing the DSS-prototype provides the decision-maker the proper tools for scaling up the selection methodology to any platform.
- The requirements on the systems level have been facilitated/fulfilled.
- The transition, within the requirement categories in table 2.2, from the stakeholders' requirements to the systems' requirements has been subjected to the standards of the design cycle.

- The numbering system within the categories [A], [B], [C] and [T] provided a shortcut for adjusting and adapting the logic blocks within the ES. This concept could be extended for future needs in maintaining and upgrading the DSS.
- The development phase issued the selection matrices in appendices A and B which form the backbone of this work. The attributes within the categories [A], [B] and [C] (*chap. 4*) are considered independent from each other. Meaning that adjusting one (sub-)attribute is not supposed to influence another (sub-)attribute.
- The DSS-prototype's reliability in supplying the wanted outcome increases with the number of performed case-studies, provided that system is improved anytime it appears to be performing sub-optimally.
- The validation phase in chapter 5 concerned case-studies with CM techniques that were technologically feasible. The CM techniques used in the case-studies were confirmed by the DSS-prototype. In addition, other CM techniques were advised and were considered technologically feasible by the prototype. However, the extent to which these selection outcomes are feasible is not validated by the present design project.

7.2 Recommendations

Finding the so-called "right solution" (i.e. the ES-based DSS) to the design problem puts in question the extent to-which the knowledge question is positively answered. The knowledge question as stated in table 3.1 reads : *"Is the selection method able to facilitate the condition-based maintenance policy?"*. The recommendations presented in this section provide some directions to which future work could make the answer to the knowledge question even more "positive".

- The selection methodology developed in this work is valid for two failure mechanisms (FM), i.e. corrosion and wear. Future work could extend the selection methodology to the remaining FM, e.g. fatigue, creep and electrical failures.
- The coherence and completeness of the attributes related to the corrosion mechanism have been validated by a corrosion expert. Future work could extend the opinion-based validation process to the attributes related to the wear mechanism.
- The reliability of the selection methodology has been improved for CM technologies that used to be the subject of the case-studies during the validation phase. Future work involving further case-studies could improve the reliability of the remaining CM techniques.

- The selection methodology could include an additional category of attributes, e.g. category [D] for commercial aspect. Such category could contain attributes such as the sensors' sensitivity, piggybackability, size and price.
- Although the requirements in table 2.2 are facilitated/fulfilled, the quality of their fulfillment could always be improved, e.g. StR21 and StR22 for readability.
- The DSS-prototype assumes that all attributes within the categories [A], [B] and [C] are independent. Linking these attributes, when applicable, adds another dimension to how CM techniques are selected, in the sense that more reliable outcomes could be anticipated.
- The validation phase considered cases where the CM strategies were technologically feasible. Future work could include cases where the economic benefits on the combination of the CM strategies are evaluated as well, especially when considering the requirements StR10, StR11 and StR12 for the financial feasibility category.

Appendix A

Selection Matrix for Corrosion Monitoring

- 0 : Prohibiting element for corresponding technique
- 1 : Recommending element for corresponding technique
- *empty* : Neutral element for corresponding technique

[illegible]

[illegible]

Appendix B

Selection Matrix for Wear Monitoring

- 0 : Prohibiting element for corresponding technique
- 1 : Recommending element for corresponding technique
- *empty* : Neutral element for corresponding technique

[illegible]

Appendix C

Corrosion Monitoring Techniques

A complete overview of the commercially-available corrosion monitoring technologies (category [T]) is provided in table (*tab. C.1*). This table is set to represent the rows of the selection matrix depicted in appendix A.

TABLE C.1: CM- and NDT techniques' sub-categories

[T01] : Mass-Loss Coupon (MLC)

[T011]	MLC - for general corrosion
[T012]	Mass-Loss Coupon for crevice corrosion
[T013]	Mass-Loss Coupon for pitting corrosion
[T014]	Stressed/precracked sheets
[T015]	Welded sheets
[T016]	Pit Initiation Analysis

[T02] : Electrical Resistance (ER)

[T021]	ER - Wire loop elements
[T022]	ER - Tube loop elements
[T023]	ER - Strip loop elements
[T024]	ER - Cylindrical elements
[T025]	ER - Spiral loop elements
[T026]	ER - Flush mount elements
[T027]	ER - Surface strip elements
[T028]	IR - Inductive Resistance Probe

[T03] : (Enhanced) Visual Inspection (VI)

[T031]	VI - Naked eye
[T032]	VI - Video camera
[T033]	VI - Micrometer
[T034]	VI - Borescope
[T035]	VI - Fiberscope
[T036]	VI - Videoscope
[T037]	VI - Liquid Penetrant Inspection
[T038]	VI - Magnetic Particle Inspection

[T04] : Linear Polarization Resistance (LPR)

Continued on next page

Table C.1 – Continued from previous page

[T05] : Galvanic Monitoring (GM)	
[T051]	GM - ZRA on Dissimilar Electrodes
[T052]	GM - ZRA on Single Electrode Array
[T053]	GM - Coupled Multi-Electrode Array
[T06] : Electrodynamic Polarization (EP)	
[T07] : Electrochemical Noise Analysis (ENA)	
[T08] : Electrochemical Impedance Spectroscopy (EIS)	
[T09] : Harmonic Distortion Analysis (HAD)	
[T10] : Acoustic Emission (EA)	
[T11] : Field Mapping (FM)	
[T12] : Guided Wave Testing (GWT)	
[T13] : Ultrasonic Testing (UT)	
[T131]	UT - Thickness Measurement
[T132]	UT - Flaw Detection
[T133]	UT - Flaw Sizing
[T14] : Electromagnetic Testing (ET)	
[T141]	ET - Eddy Current Testing
[T142]	ET - Pulsed Eddy Current Testing
[T143]	ET - Magnetic Flux Leakage
[T143]	ET - Remote Field Testing
[T15] : Radiographic Testing (RT)	
[T151]	RT - Tangential Radiography
[T152]	RT - Computed Tomography
[T153]	RT - Gamma Radiometry
[T16] : Infrared Thermography (IR-T)	
[T17] : Hydrogen Monitoring (H₂M)	
[T171]	H ₂ M - Sealed cavity H ₂ -pressure probe
[T172]	H ₂ M - Non-sealed external patch probe
[T173]	H ₂ M - Electrochemical H ₂ -patch probe
[T173]	H ₂ M - H ₂ -fuel cell probe

Continued on next page

Table C.1 – Continued from previous page

[T18] : Corrosion Potential (Ecorr)**[T19] : Water Chemistry Parameters I (WCP I)**

[T191]	WCP I - pH Measurements
[T192]	WCP I - Conductivity Measurements
[T193]	WCP I - Dissolved Oxygen
[T193]	WCP I - Oxidation-Reduction Potential

[T20] : Water Chemistry Parameters II (WCP II)

[T201]	WCP II - Alkalinity
[T202]	WCP II - Metal Ion Analysis
[T203]	WCP II - Fe-ion Analysis
[T204]	WCP II - Total Dissolved Solids
[T205]	WCP II - Chromatography
[T206]	WCP II - Residual Oxidant

[T21] : Process Parameters (PP)

[T211]	PP - Pressure Monitoring
[T212]	PP - Temperature Monitoring
[T213]	PP - Dew Point Monitoring

[T22] : Fluid Detection (FD)

[T221]	FD - Flow Regime
[T222]	FD - Flow Velocity

[T23] : Deposit Monitoring - Fouling (DM)**[T24] : Strain Measurements (SM)****[T25] : Residual Analysis (RA)**

[T251]	RA - Filming Corrosion Inhibitor Residual
[T252]	RA - Reactant Corrosion Inhibitor Residual

[T26] : Chemical Analysis of process samples (CA)

[T261]	CA - Total Acid Number (TAN)
[T262]	CA - Sulfur Content - H ₂ S
[T263]	CA - Nitrogen Content - N
[T264]	CA - Salt Content of crude oil
[T265]	CA - Chloride Content - Cl

[T27] : Microbiological Analysis (μ BA)

[T271]	μ BA - Adenosine Triphosphate Photometry
[T272]	μ BA - Fluorescence Microscopy (DAPI)

Continued on next page

Table C.1 – Continued from previous page

[T273]	μ BA - Hydrogenase Measurement
[T274]	μ BA - Radiorespirometry (SRB)
[T275]	μ BA - Antibody Fluorescence Microscopy
[T276]	μ BA - Adenosine Phosphosulfate Reductase Measurement (APS)
[T277]	μ BA - Quantitative Fluorescence in-situ Hybridization (qFISH)
[T278]	μ BA - Quantitative Real-time Polymerase Chain Reaction (qPCR)
[T279]	μ BA - Denaturing Gradient Gel Electrophoresis

Appendix D

DSS' Selection Process for EM - Remote Field Testing

DSS-CM

The DSS will take you through a series of questions regarding the selection of commercially available corrosion monitoring techniques, starting from identifying elements of the following categories :

- Category [A] : attributes related to the system of interest
- Category [B] : attributes related to the supposedly selected corrosion monitoring strategy,
- Category [C] : attributes related to the corrosion mechanism under-which the system of interest is failing

By the end of the selection process and depending on the provided input, the DSS will suggest suitable corrosion monitoring technique(s) for your system of interest.

OK**Category [A]****A1- Accessibility**

A11: Is the system of interest physically accessible?

- ☒ A111: accessible
☐ A112: non accessible

OK**Restart**

Exsys

Category [A]**A1- Accessibility**

A12: Is the system of interest accessible by extracting a representative sample?

- ☒ A121: extractable
☐ A122: non extractable

Note that the extracted sample can be gas, liquid or solid.

OK**Restart****Back**

Exsys

Category [A]

A2- Contiguity

A2: Describe the medium in which the corrosion interface takes place:

☒ A21: Gaseous Environment

☐ A22: Liquid Environment

☐ A23: Solid Environment

Exsys

Category [A]

A2- Contiguity

A21: Describe the gaseous medium in which the corrosion interface takes place:

☒ A211: O2-free environment

☐ A212: O2-bearing environment

Exsys

Category [A]

A2- Contiguity

A211: The medium is oxygen-free, describe which of the following gas(es) is (are) most likely to be responsible for the corrosion degradation:

☒ A2111: H2S/sulfur content

☐ A2112: H2

☒ A2113: Dew point

☒ A2114: Other (e.g. Chloride)

Exsys

Category [A]

A31- Material Properties

A31: The corroded part of the system of interest is mainly constructed with:

☒ A311: Metal

☐ A312: Non-metal

Exsys

Category [A]

A31- Material Properties

A311: The corroded part of the system of interest is metal-based and can be further categorized into the following:

☒ A3111: Magnetic

☐ A3112: Non-magnetic

Exsys

Category [A]

A31- Material Properties

A3111: The corroded part of the system of interest has magnetic properties and can be further categorized into the following:

☒ A31111: Ferrous

☐ A31112: Non-ferrous

Exsys

Category [A]

A32- Material Morphology

A32: Which of the following material propertie(s) is (are) the system of interest characterized by:

- ☐ A321: Porosity
- ☒ A322: Roughness
- ☐ A323: Ductility
- ☐ A324: n.a.

- Porosity:

or void fraction, is a measure of the void spaces in a material.

- Roughness:

a component of surface texture. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth.

- Ductility:

is a measure of a material's ability to undergo significant plastic deformation before rupture, which may be expressed as percent elongation or percent area reduction from a tensile test.

OK

Restart

Back

Exsys

DSS-CM

Category [B] : attributes related to the supposedly selected corrosion monitoring strategy

OK

Category [B]

B1- Background

B11: Which of the following noise(s) is (are) present in the background and is (are) significant enough to render the ongoing corrosion mechanism non-filtrable:

☐ B111: Thermal noise

☐ B112: Electric/Magnetic noise

☒ B113: Mechanical noise

☐ B114: Radioactive noise

☐ B115: Chemical noise

☐ B116: None

Category [B]

B12- Debris-bearing

B12: If applicable, does the system of interest carry debris nearby the corrosion interface?

☒ B121: Yes

☐ B122: No

☐ B123: n.a.

Exsys

Category [B]

B13- Cleanability

B13: Is the system of interest cleanable?

☒ B131: Cleanable

☐ B132: Uncleanable

Exsys

Category [B]

B14- Gradients

B14 Which of the following differential(s) is (are) present in the background:

- ☒ B141: Temperature gradient
- ☒ B142: Pressure gradient
- ☐ B143: Voltage gradient
- ☐ B144: Height gradient
- ☒ B145: Velocity gradient
- ☐ B146: None

Exsys

Category [B]

B15- Human Safety

B15: When under operation, is the system of interest safe for human activities?

- ☒ B151: Safe
- ☐ B152: Unsafe

Exsys

Category [B]

B21- Temperature Limitations

B21: Which of the following temperature intervals does the system of interest operate under:

- ☒ B211: Ambient temperature
- ☐ B212: Limited temperature
- ☐ B213: Unlimited temperature
- ☐ B214: Cryogenic temperature

B211: from 0°C to 50°C
B212: from 50°C to 300°C
B213: from 300°C to 600°C
B214: from 0°C up to -20°C

Category [B]

B22- Pressure Limitations

B22: Which of the following pressure intervals does the system of interest operate under:

☐ B221: Ambient pressure

☒ B222: Limited pressure

☐ B223: Unlimited pressure

☐ B224: (near-)Vacuum

B221: approx. 1bar
B222: up to 30bar
B223: up to 100bar
B224: less than 0.5bar

OK

Restart

Category [B]

B23- Topology

B231 The corrosion degradation takes place in a:

☒ B2311: Straight/flat topology

☐ B2312: Bended/curved topology

☐ B2313: Complex

OK

Restart

Back

Exsys

Category [B]

B23- Dimension

B232: Which of the following propertie(s) is (are) desirable to be measured for a monitoring activity:

☐ B2321: Wall thickness

☒ B2322: Cross-sectional

☐ B2323: Check the box if the system of interest is considered probe incompatible

OK

Restart

Back

Exsys

Category [B]

B24- Chemical Limitations

B24: Which of the following chemical reaction(s) does the system of interest operate under:

☐ B241: Steady state reactions

☒ B242: Redox reactions

☐ B243: Secondary reactions

☒ B244: Temperature-induced reactions

☐ B245: Pressure-induced reactions

☐ B246: None

Exsys

Category [B]

B25- Biological Limitations

B25: Does the region of interest contain biological activities that might contribute to further corrosion degradation?

☐ B251: Yes

☒ B252: No

☐ B253: n.a.

Exsys

Category [B]

B3- Diagnosis & Prognosis

B3: Which of the following monitoring capability(s) is (are) desired for an eventual CM-strategy:

☒ B31: Detecting capabilities

☒ B32: Localizing capabilities

☒ B33: Measuring capabilities

☐ B34: Predicting capabilities

Exsys

Category [B]

B4- Speed of Response

B4: For a desired CM-strategy, the speed of response should be equal or less than:

- ☐ B41: Instantly
- ☐ B42: sec-min
- ☐ B43: min-hrs
- ☐ B44: hrs-dys
- ☒ B45: dys-wks
- ☐ B46: wks-mnths
- ☐ B47: mths-yrs

DSS-CM

Category [C] : attributes related to the corrosion mechanism under-which the system of interest is failing

Category [C]

C1- Corrosion Inhibition Techniques

C1: Which of the following corrosion inhibition technique(s) is (are) applied to the region of interest:

☐ C11: Coating

☐ C12: Insulation

☒ C13: Cathodic protection

☐ C14: Chemical Inhibitors

☐ C15: None

Exsys

Category [C]

C2- Corrosion Occurrence

C2: The corrosion mechanism occurs on the:

☒ C21: Surface

☐ C22: Sub-surface

Exsys

Category [C]

C2- Corrosion Occurrence

C21: The corrosion mechanism can be described as:

☒ C211: Internal corrosion

☐ C212: External corrosion

Exsys

Category [C]

C3- Corrosion Mechanism

C3: Describe the corrosion mechanism:

☐ C31: General corrosion

☒ C32: Localized corrosion

Exsys

Category [C]

C32- Localized Corrosion

C32: Describe the localized corrosion mechanism:

☐ C321: Galvanic corrosion

☒ C322: Pitting corrosion

☐ C323: Crevice corrosion

☐ C324: Stress corrosion

☐ C325: Erosion corrosion

☐ C326: MIC

☐ C327: De-alloying / intergranular corrosion

☐ C328: High temperature corrosion

DSS-CM

Based on the provided input, the DSS suggests forming a corrosion monitoring strategy from the combination of the following technique(s) :

T016 Pit Initiation Analysis Conf=1.0

T11 Field Signal Mapping Conf=1.0

T144 EM - Remote Field Testing Conf=1.0

T191 WC I - pH Measurement Conf=1.0

Exsys

Appendix E

CBM Applicability

FIGURE E.1: Decision scheme for condition-based maintenance applicability [22]

Appendix F

Selection Process for Strain Measurements and Elastomer Compatibility Test

F.1 *Category [A]: Attributes related to the sealing mechanism:*

Attribute [A1]: Accessibility

Attribute [A11]: Physical Accessibility

- *Question:* Is the system of interest physically accessible?
- *Answer:* Accessible [A111]

Attribute [A12]: Accessibility by sample-extraction

- *Question:* Is the system of interest accessible by extracting a representative sample?
- *Answer:* Extractable [A121]
- *Question:* Describe the solid medium in which the wear mechanism takes place:
- *Answer:* Metal [A233]

Attribute [A3]: Material Properties

Attribute [A31]: Material Composition

- *Question:* The worn part of the system of interest is mainly constructed with:
- *Answer:* Non-metal [A312]
- *Question:* The worn part of the system of interest is non-metallic and can be further categorized into the following:
- *Answer:* Polymer [A3121]

Attribute [A32]: Material Morphology

- *Question:* Which of the following propertie(s) is (are) the system of interest characterized by:
- *Answer:* Porosity [A321]

Attribute [A4]: Tribology

- *Question:* Is the system of interest tribologically-related?
- *Answer:* Yes [A401]

Attribute [A41]: Lubricant Condition

- *Question:* Describe the lubricant's nature:
- *Answer:* Oil [A4111]

Attribute [A412]: Lubricated Condition

- *Question:* Is monitoring the condition of the lubricant desirable for an eventual condition monitoring strategy?
- *Answer:* Yes [A4121]

Attribute [A413]: Contaminants

- *Question:* If applicable, describe the contaminants' nature:
- *Answer:* not applicable [A4133]

Attribute [A5]: Statics

- *Question:* Describe the relative velocity under which the system of interest is operating?
- *Answer:* $V = \text{cst}$ [A512]
- *Question:* Describe the load under which the system of interest is operating?
- *Answer:* $L = \text{cst}$ [A521]

F.2 Category [B]: Attributes related to the supposedly selected CM strategy:

Attribute [B1]: Background

Attribute [B11]: Background Noise

- **Question:** Which of the following noise(s) is (are) present in the background and is (are) significant enough to render the ongoing wear mechanism non-filterable:
- **Answer:** Mechanical noise [B113]

Attribute [B12]: Debris Bearing

- **Question:** If applicable, does the system of interest carry debris nearby the worn interface?
- **Answer:** Yes (black powder) [B121]

Attribute [B13]: Cleanability

- **Question:** is the system of interest cleanable?
- **Answer:** Uncleanable [B132]

Attribute [B14]: Gradients

- **Question:** Which of the following differential(s) is (are) present in the background?
- **Answer:** Pressure gradient [B142] ; Velocity gradient [B145]

Attribute [B15]: Human Safety

- **Question:** When under operation, is the system of interest safe for human activities?
- **Answer:** Unsafe [B151]

Attribute [B2]: Physical Limitations

Attribute [B21]: Temperature Limitations

- **Question:** Which of the following temperature intervals does the system of interest operate under?
- **Answer:** Ambient temperature (between 0C to 50C) [B211]

Attribute [B22]: Pressure Limitations

- **Question:** Which of the following pressure intervals does the system of interest operate under?
- **Answer:** Unlimited temperature (up to 100 bar) [B223]

Attribute [B3]: Diagnosis & Prognosis

- *Question:* Which of the following monitoring capability(s) is (are) desired for an eventual condition monitoring strategy:
- *Answer:* Detecting capabilities [B31] ; Predicting capabilities [B34]
- *Question:* An eventual condition monitoring strategy is to predict the wear mechanism with a:
- *Answer:* Non-linear growth [B342]

Attribute [B4]: Speed of Response

- *Question:* For a desired condition monitoring strategy, the speed of response should be less or equal than:
- *Answer:* wks-mnths [B46]

F.3 Category [C]: Attributes related to the wear mechanism

Attribute [C1]: Wear Mechanism

- *Question:* Describe the wear mechanism:
- *Answer:* Abrasive wear [C12]

Attribute [T]: CM and/or NDT Techniques Based upon the provided input, the DSS advises in the following CM-strategy:

- *Strain Measurement* [T24]
- *Elastomer Compatibility Test* [T702]

Bibliography

- [1] "20 Years on lessons learned from Piper Alpha. The evolution of concurrent and inherently safe design". In: *J. Loss Prev. Process Ind.* "23" (2010), pp. 936–953.
- [2] ABS. "Guidance notes on equipment condition monitoring techniques". American Bureau of Shipping. ABS, 2016.
- [3] *Acoustic emission for corrosion detection*. Middle east nondestructive testing conference and exhibition. Manama, Bahrain: 3rd MENDT, 2005.
- [4] H. Akkermans. "Rondetafel 6 : Condition-Based Maintenance, een kwestie van tijd". In: "World Class Maintenance" (2017). URL: <https://www.worldclassmaintenance.com/knowledge/rondetafel-6-2017-condition-based-maintenance-een-kwestie-van-tijd/>.
- [5] I. Alexander. "A taxonomy of stakeholders: Human roles in systems development". In: *Int. J. Technol. Human Interact.* (2005), 23–59.
- [6] R. Atkinson. "Project management: cost, time and quality, two best guesses and a phenomenon, its time to accept other success criteria". In: *International Journal of Project Management* 17.06 (1999), pp. 337–342.
- [7] R. S. Beebe. *Predictive Maintenance of Pumps Using Condition Monitoring*. Elsevier Science Technology Books, 2014.
- [8] R. Bogue. "Sensors for condition monitoring: a review of technologies and applications". In: *Emerald Group Publishing Limited* (2013). URL: <https://www.emeraldinsight.com/doi/abs/10.1108/SR-05-2013-675>.
- [9] H. Bohni. *Corrosion Mechanisms*. Mercel Dekker Inc., 1987. Chap. 6, 285–326.
- [10] S. Braun. "Mechanical Signature Analysis: Theory and Applications". In: *Academic Press Mechanical Signature Analysis* (1986).
- [11] "CAMPIONE Congres: Smart Society is de toekomst". In: *World Class Maintenance* (2017). URL: <https://www.worldclassmaintenance.com/campione-congres-smart-society-is-de-toekomst/>.
- [12] *Case study - Corrosion monitoring in marine environment in Croatia*. Faculty of Civil Engineering University of Zagreb, 2015.
- [13] "Condition-Based Maintenance is geen keuze meer". In: "World Class Maintenance" (2017). URL: <https://www.worldclassmaintenance.com/condition-based-maintenance-is-geen-keuze-meer/>.

- [14] "Condition Monitoring Methods and Economics". In: *Bruel and kjaer*. (1975).
- [15] P. Cristiani. *Corrosion Techniques*. Woodhead publishing in materials, 2008. Chap. 15, 347–387.
- [16] "Decision Support Systems and Expert Systems: A Comparison". In: *Elsevier Science Publishers* (1985), pp. 21–26.
- [17] "Design for Maintenance". "Guidelines to enhance maintainability, reliability and supportability of industrial products". Enschede, The Netherlands: "University of Twente", 2012.
- [18] E. Hull J. Dick, K. Jackson. "Requirements Engineering". 3rd. Springer.
- [19] European Sealing Association ESA. *Successfull sealing with elastomers*. ESA, Gwynedd LL57 4PL, UK, 2010.
- [20] Funke. *Corrosion Basics: an introduction*. 1440 South Creek Drive, Houston, Texas 77084 (USA): National Association of Corrosion Engineers (NACE), 1984.
- [21] "Growing towards PBL Contracting". "Mannaging Maintenance Repear and Overhaul". "World Class Maintenance Consortium". URL: <https://www.worldclassmaintenance.com/publicaties/growing-towards-pbl-contracting/>.
- [22] *Guidelines for Condition-based Maintenance*. Research. NLDA, Gasunie, Wärtsilä, 2009.
- [23] P. M. Lugt. *GREASE LUBRICATION IN ROLLING BEARINGS*. A John Wiley Sons, Ltd., Publication., 2013. Chap. 16, 327–336.
- [24] J Moubray. *Reliability Centered Maintenance*. Aladon, 2001.
- [25] D.Wallace M.V. Zelkowitz. "Experimental models for validating technology". In: *IEEE* 31.05 (1998), pp. 23–31.
- [26] NASA. "Why metals corrode?" In: "Corrosion Technology Laboratory" (2005). URL: https://corrosion.ksc.nasa.gov/corr_metal.htm.
- [27] P. Nguyen N. Bich. *Corrosion monitoring using the field signature method inspection tool (FSM-IT)*. Pangea Solutions Inc, Canada. Chap. 28, pp. 658–670.
- [28] "Performance Based Contracting". "Waarom, wanneer, wat, hoe?" "World Class Maintenance Consortium". URL: <https://www.worldclassmaintenance.com/publicaties/performance-based-contracting/>.
- [29] *pF interval*. <https://www.efficientplantmag.com/2017/10/profitable-reliability-control-horizon/>. Accessed: 14-12-2017.
- [30] B. N. Popov. *Corrosion Engineering Principles and Solved Problems*. Elsevier, 2015. Chap. 6, 239–287. URL: <https://www.sciencedirect.com/science/article/pii/B9780444627223000069>.

- [31] NACE International Publication. *"Techniques for Monitoring Corrosion and Related Parameters in Field Applications"*. Item No. 24203. NACE International, 2013.
- [32] P. R. Roberge. *Corrosion Inspection and Monitoring*; Royal Military College of Canada - Ontario, Canada: Wiley Interscience - A John Wiley Sons, Inc., Publication, 2007.
- [33] Beebe. RS. *Machine condition monitoring MCM Consultants*. 2001.
- [34] M. J. Ryan. "An Improved Taxonomy for Major Needs and Requirements Artifacts". In: *INCOSE* (2013), pp. 244–258.
- [35] Y. P. Salamatov. *TRIZ: the Right Solution at the Right Time: a guide to innovative problem solving*. Hattem, The Netherlands: Insytec B.V., 1999.
- [36] System seals. *Failure Analysis Guide, Eliminate Potential and Future Problems*. USA, 2015. URL: http://www.systemseals.com/wp-content/uploads/2014/12/3050_System_Seals_Failure_Handbook.pdf.
- [37] *Systems Engineering and Analysis*; Version 5th. Upper Saddle River, New Jersey: Prentice Hall, 2011. URL: <http://www.pearsoned.co.uk/bookshop/detail.asp?item=100000000374477>.
- [38] *The Business Dictionary*. <http://www.businessdictionary.com/definition/stakeholder.html>. Accessed: 28-02-2018.
- [39] "The effect of corrosion induced surface morphology changes on ultrasonically monitored corrosion rates". In: *"Smart Mater. Struct"* "25" (2016). URL: "<http://iopscience.iop.org/article/10.1088/0964-1726/25/11/115010/meta>".
- [40] *The Law Dictionary*. <https://thelawdictionary.org/stakeholders/>. Accessed: 28-02-2018.
- [41] T. Tinga. *Mechanism Based Failure Analysis*. Nederlandse Defensie Academie, 2012.
- [42] J. Shang B. Bridge T.P. Sattar H.E. Leon Rodriguez. "Automated NDT of Floating Production Storage Oil Tanks with a Swimming and Climbing Robot". In: (2006), pp. 935–942.
- [43] *Understanding Decision Support Systems and Expert System*. Irwin Inc., 1994. Chap. 4, pp. 102–105.
- [44] Wartsila *Dynamic Maintenance Planning and Condition-based Maintenance*. Presentation. 2014.
- [45] R. J. Wieringa. *"Design Science Methodology"*. Springer, 2014.
- [46] Y. Zhang et al. "Sealing Mechanism and Failure Analysis of Actuator Reciprocating Seal". In: *IEEE* (2016), 2190—2195.