The background of the entire image is a close-up photograph of a heavily corroded metal surface. The texture is rough and uneven, with various shades of brown, orange, and dark grey. The corrosion appears as dark, irregular patches and pits, particularly concentrated in the lower half of the image. A dark, semi-transparent horizontal band is overlaid on the upper portion of the image, serving as a background for the title text.

FAME X

Failure Mechanism Identification Expert System

DIMITRIOS KARAMELAS

FAME-X

FAILURE MECHANISM IDENTIFICATION

EXPERT SYSTEM

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**Chairman and Director of PDEng
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FAILURE MECHANISM IDENTIFICATION
EXPERT SYSTEM

PDEng Thesis

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*Dedicated to my parents, who taught me what personal sacrifice is,
to my grandfather who taught me what pride is and
to my sister who taught me what strength is.*

*Αφιερώνεται στους γονείς μου που μου δίδαξαν τι σημαίνει αυτοθυσία,
στον παππού μου που μου δίδαξε τι σημαίνει περηφάνια και
στην αδερφή μου που μου δίδαξε τι σημαίνει δύναμη*

SUMMARY

Although maintenance tries to prevent them, failures regularly occur in practice. Prevention prerequisites insight on “how” a failure occurs. Failure mechanisms (FM) describe how components fail. However, operators or technicians as the first people to deal with a failure, normally lack the knowledge to assess FM that act on a material level. Current failure reporting is typically done by entering a failure type/failure mode/cause manually or selecting from a drop-down menu. However, this process has been reported as problematic by several industries. The current thesis attempts to propose a treatment for the above problematic area which is addressed in the first chapter.

Many companies face the same failure reporting problem. Several have been approached to discuss their needs and the means to satisfy them. Chapter 2 presents the stakeholders of this project and identifies their needs in different levels.

The treatment proposed here is the FAME-X Expert System (ES) which is designed to assist operators in assessing the appropriate FM. Operators can access FAME-X from their mobile devices via the Web and perform an on-site failure analysis. Chapter 3 introduces the idea behind the ES which is simply that failure analysis expertise is transferred from a human to a computer in the form of heuristics. This knowledge is then stored in the computer and users call upon the computer for specific advice as needed. The computer asks questions regarding failure diagnostic characteristics, makes inferences and arrives at a specific conclusion. Then, like a human consultant, it gives advices on the most dominant FM given the provided evidence and explains, if necessary, the logic behind the advice.

Chapter 4 defines the design cycle of FAME-X which is composed by the following tasks: problem investigation, treatment design and treatment validation. The structure of the thesis corresponds to these tasks. The content of Chapters 1 until 3 is dedicated to problem investigation. The rest of the chapters are addressing the two remaining tasks.

The actual design of FAME-X (i.e. treatment design) starts in Chapter 5 where the requirements for the design are set. FAME-X system is based on an extensive study of failure diagnostic characteristics and their contribution to FM. In contrast to failure modes, the proposed FM approach enhances the decision making upon proper remedial actions. Chapter 6 formulates the failure analysis knowledge which is then transformed into heuristics in order to be able to be inserted into the computer. The detailed design of the computer is presented in Chapter 8 where the various modules comprising an ES are developed an intergraded. This chapter concludes the treatment design phase.

The last phase of design, treatment validation, takes place in Chapter 8 and Chapter 9. Various methods are used for the validation of FAME-X that include expert opinion and experiments with various users. They test its diagnostic accuracy and capture the experience of using FAME-X as described by the users. At last, FAME-X’s layout and its properties are presented. The conformity of the prototype to the initial requirements is explored. The design cycle closes with a discussion regarding the techno-economic feasibility and the sociotechnical embedding of FAME-X.

FAME-X can help standardize failure mechanism identification for a given set of characteristics, unify failure terminology, and codify and document the failure investigation procedure. This standardized registration will then largely improve the reliability engineering and data analytics activities that are based on this data. These are some of the most important conclusions which are given in the final chapter together with guidelines for further research and improvement of the diagnostic system FAME-X.

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ACRONYMS

AI	Artificial intelligence
ANN	Artificial neural networks
CB	Command block(s)
CBR	Case-based reasoning
CMMS	Computerized maintenance management system
DSS	Decision support system(s)
ERC	European reliability center
ES	Expert system(s)
FA	Failure analysis
FM	Failure mechanism(s)
FMECA	Failure mode and effect analysis
GUI	Graphical user interface
HCF	High cycle fatigue
IA	Intelligent agents
LB	Logic block(s)
LCF	Low cycle fatigue
NS	Nederlandse Spoorwegen
OEM	Original equipment manufacturer
PDEng	Professional doctorate in engineering
RBR	Rule-based reasoning
RCA	Root cause analysis
RCM	Reliability Centered Maintenance
SCC	Stress corrosion cracking
TAR	Technical action research
VB	Visual basic

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

1.1.1 Niches in the field of maintenance

Throughout the years, the importance of the maintenance function has grown. Optimization of maintenance plans yields significant benefits for industries. During the previous decades, maintenance was considered to be a necessary ‘evil’ by the majority of companies. A procedure that must be followed in order to avoid unexpected failures. A conservative practice that evidently has high cost. However, this old-fashioned mentality has gone through big changes in the last years, especially in large organizations. Industrial maintenance has shifted from conventional methods, like run-to-failure maintenance or preventive maintenance to condition based maintenance and predictive maintenance. For the practice of the last two, it is mandatory to better understand the condition of the asset. Hence, many projects are funded to research new ways for condition monitoring and failure diagnosis.

Being in a new technological era where internet of things is taking place in every aspect of people’s lives, maintenance could not stay apart from it. The use of mobile devices, like tablets, in maintenance operations is rather a common practice nowadays, especially in large organizations. These devices can use complex artificial intelligence algorithms which can guide, advice and organize tasks for the technicians during the diagnostic and restoration process.

1.1.2 The failure reporting problem

The objective of maintenance is to reduce or even to eliminate sudden unexpected failures. However, in order to eliminate failures it is important to know at first what is causing them. The first people to deal with a failure of a machine are the operators. Apart from fixing the problem, they also have to file a report regarding the nature of the failure. Nowadays, in most industries this is typically done by entering a failure type or a failure mode or a cause manually or selecting from a drop-down menu. However, this process has been identified quite problematic due to:

- the intuitive and empirical nature of the decisions,
- the high dependency on the experience of the maintainer/technician for the diagnosis,
- the lack of skills of a maintainer/technician to understand what is taking place inside the material,
- the lack of motivation of the maintainers/technicians to perform the task of diagnosis,

- the lack of uniform terminology on failures which leads to misunderstandings,
- the use of free language that leads to confusion or misunderstandings,
- and the use of handwriting on paper that probably will be eventually lost.

Consequently, most of the time the report is filled with inaccurate data or a simple “I don’t know”. All the above lead to absent or – even worse – unreliable data essential for the analysis and decision making for proper remedial actions. Even in cases of a correct diagnosis, the data are used temporarily but they are not preserved within companies in the long term. When people leave a company, they take their knowledge and experience with them. The newcomers having to deal with a failure that probably has been seen before in the past, have to diagnose it and resolve it from scratch. For example, NS engineers urged for the need of knowledge preservation within NS. They said: “We have to keep the knowledge of the people in-house and to transfer it to the coming generations. Consulting experts are too expensive to have.”

Failures of engineering components are a frequent phenomenon in any type of industry. Especially when the root cause is not diagnosed correctly, failure can be recurring. Their impact varies significantly depending on the type of the failed component and its importance. Some failures need extensive analysis to be diagnosed while others can be quite tedious. It is economically fair to consult an expert for high impact and complex failures. However, in all other cases an expert is unaffordable. Hence, a substitution of the physical presence of the expert should take place, without, substituting his or her expertise. This leads into formulating the objective of the PDEng project which is introduced in Section 1.3.

Defining the type of knowledge essential for permanently resolving industrial failures is not always straight forward. Is a failure mode enough for deciding on proper remedial action? Is the knowledge of the dominant failure mechanism enough on its own to decide on proper remedial action? How to identify fatigue or corrosion or wear macroscopically? These are important questions that trouble many maintenance managers. However, before deciding which information is important, it is wise to define failure and other subsequent terms that are used extensively in this work.

1.2 DEFINING FAILURE

A well-defined problem is half way solved. Hence, the definition of terms is critical as a starting point. Definitions for failure, failure mechanism, failure mode, root cause, failure analysis, and root cause analysis are given here so that the terminology can be understood and interpreted correctly where used throughout the thesis.

Failure will be considered as the state of a part or a system in which it can no longer fulfil its intended function. Therefore, failure does not always imply the physical failure of a part, like fractured, but could also be the result of wastage blocking a nozzle leading to flow reduction. *Failure analysis* is the critical process in determining the physical root causes of problems. It is a complex process, draws upon different disciplines, and uses a variety of observation, inspection, and laboratory techniques all contributing to failure diagnosis.

Failure can be diagnosed in different levels. Failure of a specific part or subsystem does not automatically imply that the complete system fails. A broken blade in a turbine engine of an

aircraft does not mean that the whole turbine failed, neither that the plane will crash. In that case, the failure is on a part (blade), but no failure occurs on the system (turbine). In Chapter 6, the failure level that the proposed system is operating on is defined in detail.

Another important issue when describing failures, and fundamental for this work, is that a clear distinction should be made between failure mode and failure mechanism. The *failure mode*, according to the ISO 14224:2006 [1], is the effect by which a failure is observed on the failed item. ISO 14224:2016 [2] defines it as the manner in which a failure occurs. This means that the failure modes are generally related to the performance requirements of the system, as Tinga [3] states. Performance can have the following classes [4]:

- *Intermittent no/full operation* means that the failure only causes random occasional periods where functionality is completely affected.
- *Intermittent degraded/full operation* means that the failure only causes random occasional periods where functionality is partially affected.
- *Intermittent no/degraded operation* means that the failure causes random occasional periods where functionality is completely affected and others where functionality is partially affected.

Examples of failure modes are the discoloration of a stainless steel due to corrosion, the excessive vibration of a shaft due to misalignment and the cracking of a bearing inner ring due to rolling contact fatigue.

Failure modes have several levels of hierarchy and an abstract level of detail. The failure of the turbine engine of an aircraft is a failure mode of a high hierarchy level. The failure of the blade of the turbine engine is a failure mode of a lower hierarchy level. Reliability Centered Maintenance (RCM) standards [5] state that failures shall be identified at a level of causation that makes it possible to identify an appropriate failure management policy.

At the lowest hierarchy level, the component level, failure modes can be attributed to non-physical and physical failures causes. The non-physical failure causes are mostly due to human errors, for example, the contamination of a lubricant with dust due to wrong opening of the lubricant container. In this case, the lubricant fails without any actual failure taking place. On the other hand, physical failures are due to physical, chemical or other processes or mechanisms yielding degradation of the component and ultimately leading to the physical failure [3]. This process is called *failure mechanism*. The term describes “how” the equipment failed.

As the definition implies, failure mechanisms are well defined, they always act on a component, or more specifically, material level and their effects can be described by mathematical models (e.g. crack propagations models, corrosion rate models, wear models). An important observation regarding failure mechanisms is that they are limited in number. More than one failure mechanisms can contribute to the development of one specific failure mode. However, the number of possible mechanisms is much smaller than the almost infinite number of failure modes that can be defined for all possible systems, subsystems and components [3]. A more extensive reference to each type of failure mechanism will be introduced in Chapter 6.

The failure mechanisms explains “how” a component failed and it is a process related to material deterioration. The “why” is described by the *root cause* of the failure. This is the final and absolute level of causation. Root causes can be quite obscure and not immediately apparent, and may require significant investigation, or *root cause analysis*, for the underlying reasons to be revealed [6]. Root cause analysis will be treated extensively in Chapter 6. Root causes are attributed to three levels, namely, physical roots, human roots and latent roots [7]. These levels or root cause are best defined by the two examples in Table 1-1. The critical definitions and discussion around failure assist the reader to understand the design problem which is introduced in the next section.

Table 1.1. Examples of various types of root causes

Root type	Pressure vessel failure	Bolt failure
Physical roots	Corrosion damage, wall thinning	Fatigue crack; equipment vibration; lack of vibration; isolation
Human roots	Inadequate design performed	Improper equipment installed
Latent roots	Inadequate inspector training	Inadequate specification verification

1.3 APPROACH AND OBJECTIVES

1.3.1 Description of the design challenge

Design science, which is the core of the PDEng program, concerns the design and investigation of artifacts in context. The artifacts to designed and studied are, for example, methods, techniques, notations, and algorithms used in software and information systems. The context for these artifacts is the design, development, maintenance, and use of software and information systems. Since our artifacts are designed for this context, we should investigate them in this context. The artifacts interact with the problem context in order to improve something in that context. The current project is calling for the design of *a decision support tool for failure mechanism identification*. In this case, the tool will interact with the users in an industrial environment, via a mobile device, in order to perform failure analysis, identify a failure mechanism and, ultimately, improve failure registration. Figure 1-1 shows the interaction of the artifacts with the context as imagined for the current design problem.

The two parts of design science, design and investigation, correspond to two kinds of research problems in design science, namely, *design problems* and *knowledge questions* [2]. The *Design problem (DP)* here is how to design a tool that will interact with its context in order to improve failure registration. Design problems call for changes and they have usually many different solutions. These are evaluated by their utility and with respect to the stakeholder goals. Consequently, there is not one single best solution for a design problem. Two main goals of the thesis are (i) to investigate how to design a Decision Support (DS) tool which can contribute to the stakeholder goals in the most effective way and (ii) design this tool.

Knowledge questions (KQ), opposingly, do not call for changes but ask for knowledge. The answer is usually unique and can be given partially, with uncertainty, or wrongly. However, it is evaluated by the truth. And the truth can be only one for each KQ; it does not depend on

stakeholders goals. Some knowledge questions, already introduced in Section 1.1.2, are: “Is a failure mode enough for deciding on proper remedial action?”, “Is the knowledge of the dominant failure mechanism enough on its own to decide on proper remedial action?”, “How to identify fatigue or corrosion or wear macroscopically?”. So an additional goal of this thesis is to answer the knowledge questions relevant for the problem at hand.

The two type of goals are not separate from each other; they connect during the design iteration. Designing a DS tool for failure analysis requires an analysis of the tool, the failure analysis procedure, the user and the environment in which the tool will be used. Answering KQ returns knowledge to solve the design problem which can lead to new design problems (for example, how to design a prototype DS tool and how to employ it in a specific industry). Subsequently, the prototype can be returned back to the question answering activity and help answering other knowledge questions.

Figure 1-1. The subject of design science: An artifact interacting with its context.

1.3.2 Objectives of the design project

This project has two objectives. The first is to design a DS tool for failure mechanism identification. The failure analysis is assumed to involve only mechanical components. The goal of the analysis is to identify the failure mechanism describing the component’s failure. Hence, the failure mechanisms to be identified are the most common for mechanical components. The DS tool will be used by non-expert technicians in failure analysis who will access it via a mobile device.

Secondly, this project intends to give answer to the knowledge questions emerging from the design problem. During the design process usually multiple knowledge questions are emerging. However, there are two high level questions which will be answered:

- which information regarding a failure are needed to decide upon proper remedial action?
- how to perform a macroscopic failure analysis of mechanical components?

The answers to these questions are the bases for the design of the DS tool for failure analysis.

1.3.3 Approach

In order to accomplish the design objectives, the PDEng project iterates over the activities of designing an artifact and investigating its interaction with the problem context. The mechanisms in which tackles the problem is called “treatment”. The word “treatment” is adopted from Wierigna [8] and it is used to replace the word “solution” which engineers tend to extensively use. This is because solution could mean that the problem is partially solved. Treatment as a medical term suggests the interaction of the medicine with the human body for healing a disease. Accordingly, the decision support tool to be designed is to treat the failure reporting problem.

The design task itself is decomposed into three tasks, namely, *problem investigation*, *treatment design*, and *treatment validation*. These tasks are called the *design cycle*, as designers iterates over them multiple times during design projects. More details on the design cycle are given in Chapter 4. The design tasks or phases are the skeleton of this thesis and they are structuring the chapters accordingly. The thesis layout is introduced in the following section.

1.4 THESIS LAYOUT

In the present chapter, the background of the failure reporting problem and the motivation for this project is acquainted to the reader. Definitions of failure and its different forms are given to set the basic vocabulary of the thesis. The chapter concludes by formulating the objective of the thesis which is to investigate how to design a DS tool which can contribute to the stakeholder goals in the most effective way and to actually design this tool. Chapter 2 identifies the stakeholders of this project and their needs. These needs set the basis for the requirements that the design is to satisfy. An exploration of the possible treatments that could satisfy the needs is taking place in Chapter 3. There, Decision Support Systems (DSS) and one of its subcategories, i.e. Expert Systems (ES) which are specialized to mimic human expertise, are introduced. Together with the previous chapters, Chapter 3 constitute the *problem investigation* design phase. This phase is completed with the decision to design an Expert System entitled as FAME-X.

The next phase, *treatment design*, describes the development of the FAME-X system. It begins with Chapter 4 which defines in detail the design cycles and the development steps for the realization of the treatment. In Chapter 5 the previously described needs are formally transformed into requirements. The most important step for the design of the system which focus on the gathering and structuring the problem solving knowledge are described in Chapter 6. The realization of the tool takes place in Chapter 7 which finalizes the treatment design phase.

The system to be designed is validated by different techniques in Chapter 8 which introduces the reader to the *treatment validation* phase. The design cycle concludes in Chapter 9 where the prototype system is presented, and its properties are discussed and checked against the requirements of the stakeholders. Finally, important conclusions drawn from the investigation of the treatment interacting with the problem context are described in Chapter 10. The thesis comes to an end by setting design guidelines on improving the current treatment.

CHAPTER 2

STAKEHOLDERS ANALYSIS

2.1 INTRODUCTION

In the early stages of the project, several discussions were performed with different industries in order to identify the needs for the decision support tool. The companies expressed some generic wishes, but also some needs that were very focused to their interests. This valuable input was collected and distilled. The needs that comply with the generic nature of the project were kept and respected during the design. The more specific needs assisted in establishing the required mindset for the design of such a tool that ensures its applicability. To that respect, this chapter firstly identifies and presents the stakeholders and then documents their needs in different levels.

2.1.1 Stakeholder collaboration framework

Most PDEng projects are funded by specific companies. The funders have a direct interest in the PDEng project which has been created in order to treat some specific need. Besides the financial support, the company provides also technical support, guidance and mentorship to the PDEng candidate. Frequent meetings and close collaboration are there to ensure that the final design will satisfy the initial requirements and needs.

In contrast to the usual collaboration framework, this project has a more generic approach and pluralistic input. Different companies are involved in different aspects of the project. During the problem investigation phase, before anything was designed and requirements were established, discussions were performed with various companies in order to identify, describe, explain and evaluate the problem. These discussions assisted in requirement formulation and in proper design guidelines establishment. Furthermore, the companies were involved in the final phase of design which is the implementation and validation of the design. Case studies of real world failures experienced by the partners were carried out to evaluate and improve the design. In addition, the design was evaluated by implementing it in its intended environment and by expert's opinion.

2.2 STAKEHOLDERS AND THEIR NEEDS

Before any system can be developed it is essential to establish the need for the system. If the purpose of a system is not known, it is unclear what sort of system will be developed, and it is impossible to determine whether the system will satisfy the needs of its users when it is developed [9].

Here, the stakeholders of the design project are presented in Table 2-1. The stakeholders are mainly from the University of Twente and from several companies. In order to acquire a better

insight into the failure registration problem of the company stakeholders, a questionnaire was handed to them before the in person interviews. The questionnaire, which can be found in Appendix, and the interviews revealed the current practices and needs of the stakeholders. The findings are discussed below.

Table 2-1. Stakeholders of the design project.

Stakeholders	Description
World Class Maintenance (WCM)	Funding organization
University of Twente	Supervisors of the project
NS	Potential client, user, consultant
TATA Steel	Potential client, user, consultant
Strukton	Potential client, user, consultant
ERC	Potential client, user, consultant, negative stakeholder

World Class Maintenance (WCM)

WCM is the network for 'smart maintenance' in the Netherlands. They carry out cross-sectoral innovation projects, develop educational program and work on an active network in which asset owners, service providers, knowledge and research institutes and the government participate. In that perspective, they are funding this PDEng project. Besides financial support, WCM has no other involvement in the project.

University of Twente (UT)

University of Twente is a public research university located in Enschede, Netherlands. It offers degrees in the fields of social sciences, exact sciences and is highly specialized in engineering. The University is committed to making economic and social contributions to the Netherlands. Therefore, the entrepreneurial spirit is one of the core values of the institution. UT is where the design project is mostly taking place.

Nederlandse Spoorwegen (NS)

NS is the principal passenger railway operator in the Netherlands. It provides rail services on the Dutch main rail network (hoofddrailnet). Due its aging and costly assets, NS is investing heavily in asset and maintenance management. It is also one of the participating companies of the WCM consortium. NS trains are operated daily. Hence, failure is inevitable. As they are trying to gain better insight into failures, they expressed interest for the project.

Contacts within NS urged for better understanding of failures, pointed out the difficulties they had in failure data collection and emphasized on knowledge preservation within the company. For this, they initialized a project named "*Kennisbank*" (Knowledge bank) in order to develop a database where information regarding failure mechanisms will be stored. The database is intended to provide engineers a quick access to information and fixed terminology to avoid miscommunication.

Furthermore, NS maintenance engineers explained the current failure reporting procedures. This is based on selection of the failure mode from a drop down menu. Moreover, some of the failure modes are controlled by an automatic alarm system. However, failure mechanism identification is not targeted by the engineers. In cases of repetitive and severe failure with high economical and safety impact, they turned to specialized external consultancy to obtain an extensive failure and root cause analysis by experts. However, these procedures rarely take

place as they can be of large cost. Thus, a link between the company's needs and the project's goals was established. Several meetings were conducted to discuss the requirements of a failure analysis system. NS also provided a case study as to be used for the validation of the design. The case study is described in more detail in Chapter 8.

TATA Steel

Tata Steel Europe Ltd. is a steelmaking company headquartered in London, United Kingdom, with its main operations in the United Kingdom and the Netherlands (in IJmuiden). It is one of the top steel producing companies globally. TATA has a 24/7 production of steel which requires expensive and large size assets. Hence, maintenance optimization is financially crucial for the company.

The contact with the company was established via a principal consultant in asset management. In a meeting together with other highly experienced maintenance engineers for various departments they express the need to eliminate the intuitive factor during failure diagnosis. The current reports were based on failure modes and not on failure mechanisms. Guidelines on failures based on ISO 14224 [1], aiming to distinguish failure modes, failure mechanisms and root causes existed in the TATA's books. However, the selection among all the previous categories was done based on experience and judgement of the technician. With insufficient knowledge in failure analysis and without a proper guidance during failure analysis, the generated failure reports are poor in information and untrustworthy.

TATA's maintenance engineers were willing to improve current reporting procedures and, to that context, they expressed their interest for a system tailored to their needs; a system capable for root causes analysis. Given the generic nature of the proposed system and the failure mechanism approach, there was not a perfect match between the company's needs and the project's design line. However, the collaboration was continued and TATA assisted in the implementation and validation phase of the design.

Strukton Rail

Strukton Rail is a full-service and technology provider for railway systems. They design, build and maintain rail infrastructure and rolling stock systems with the mission to make rail transport a more competitive, safe and reliable option. They are responsible for the maintenance of the Dutch rails, electrical switches and crossings which are owned by NS. A meeting with an experienced maintenance engineer held in the beginning of the project provided insight on the company's procedures and needs regarding failure reporting.

Failure analysis is one of the main tasks of the people of Strukton. Failure registration is performed in a computerized system called "SOS". The reports contain only failure modes and they are usually filled in with free text via portable devices used by the technicians. The failure mechanism is only identified by a condition monitoring system or detailed inspection by a "technical specialist". In some occasions, the OEM is also consulted.

Strukton is keen to improve registration quality. In this way, the accurately diagnosed and reported failures could be linked to the identified failures registered in their FMECAs. This could improve significantly the current failure management.

To resolve these issues, Strukton needed a more structured and intelligent way to perform failure registration. These characteristics were seen in the tool proposed here. At last, for them, the most interesting part of this project was the methodology used to design the tool and the governing principles.

European Reliability Center (ERC)

The European Reliability Center (ERC) is a company focusing on reliability centered maintenance (RCM). ERC has developed and implemented successfully to several companies "DORA", a software code used to build and develop new or existing maintenance plans that are used in the Computerized Maintenance Management System (CMMS).

Opportunities for further collaboration are explored between ERC and the author of this document based on the mutual targets of DORA and the decision support tool. DORA has an interface where it assists the user in performing FMECAs and RCAs by offering a structured way of handling failure related information. The user is responsible to collect the data regarding failure characteristics, identify failure modes and failure mechanisms and register them. The input given to the system is selected by the user. For example, a failure mode or a failure mechanism is selected from a drop down menu. Also, there is no intelligence that will diagnose the root cause of a failure. The user performs the various analyses and DORA provides an easy and structured way for this. However, the input could be improved if intelligence is introduced to the system. This can be provided by the treatment proposed here. Hence, discussions are taking place regarding the possibility of integrating the treatment to DORA.

As a potential partner, ERC is recognized as positive stakeholder. However, ERC, as a software development company, could develop its own failure analysis module. In this case, ERC would be a negative stakeholder of the project due to competition reasons. Negative stakeholders are equally important as positive stakeholders to recognize in a project.

2.3 NEEDS AT DIFFERENT LEVELS

The previous section reflects the needs of the stakeholders as they were imposed in series of meetings and discussions. Some of the needs are expressed explicitly and other can be deducted by the description of the problem context and the desired artifact. An attempt to organize all the previous needs according to the various levels of INCOSE [10] guidelines is following.

Enterprise level

The enterprises involved in the project are the University of Twente which promotes the design project and companies that they are interested to adopt the system. UT promotes high end research, innovative and challenging ideas that will convert effectively to economic industrial solutions. Companies invest in maintenance related projects as an effort to reduce current costs and maximize efficiency. Hence, the industrial prestige of the tool and cost reduction are the identified needs in the enterprise level.

Business management level

UT is the most entrepreneurial university of the Netherlands. Therefore, it is considered important to transform ideas into business cases. The development of a business case around the ES comes in line with the UT's mission and constitutes a desire for almost every project. A bottleneck for industrial managers is the knowledge elicitation, preservation and transformation to the next generation of employees. Nederlandse Spoorwegen (NS) explicitly stated the need to preserve the knowledge on failures built throughout the years and transfer it to the next generations that will be employed. In addition, aspects such as the adaptability and the applicability of the system are very important for their business processes. At last, the system has to be easily and affordably maintained.

Business operations level

Stakeholders demand an innovative, industry applicable and fully operating system when delivered, at the end of the two year PDEng program. The company peers need a system that will have an immediate effect in optimizing maintenance planning. This can be done by having more accurate and structured failure data. Technicians require guidance to perform failure analysis and decide upon the acting failure mechanism. This can be done via the mobile devices they are using by implementing a failure analysis module. The collected data will help to archive failure in a more efficient and informative way. Then, failure incidents can be linked to FMECAs. This will provide insight to the effects of a failure to the different business levels. Consequently, the decision making process will become more efficient.

System level

The system's goal is the generation of accurate and structured information capable of providing insight into a mechanical failure. The information should be provided within a limited amount of time and with certain validity.

In addition, the tool is intended to be operated on the mobile devices (tablets) of technicians or maintainers. Hence, the tool should be integrated easily and effectively with other hardware and software. The system should be designed in a way that enables high maintainability. Moreover, the intended users are technically experienced people with, however, limited knowledge on physics of failure and root cause analysis. Companies are reporting that their employees work hard to restore failures and there might not be enough time or motivation to use a failure analysis system. For this, "user-friendliness" and time spend on using the system are important aspects that should be addressed.

System elements level

Every system is comprised by various system elements with different functions and, hence, different needs. The stakeholders impose their needs regarding the some obvious elements that an imaginary decision support tool could have. These needs are presented below.

The memory of the tool should have enough capacity to store failure data for a considerable amount of time. Also, the memory, in case it accessed by multiple users, should maintain the integrity and consistency of their data.

Furthermore, a Graphical User Interface should allow the communication of the tool with the user.

Since the decision support is intended for non-experts, simplicity, readability, effectiveness, comprehensibility and supportability are essential aspects for a potential GUI. As a crucial system element, it contributes significantly to the opinion the user formulates for the tool and, therefore, it can motivate the user to engage with the tool.

The users can also be motivated to engage with the tool when portability is ensured. The design should be as such that the tool can be run on mobile devices and computers. In this way, failure investigation could be done when and where it is needed. Equally important for the user is the capability of the tool to demonstrate the logic behind its decisions. In this way, diagnosis can be checked with experts for potential errors.

CHAPTER 3

DECISION SUPPORT SYSTEMS (DSS)

3.1 INTRODUCTION

In the previous chapter the needs of the stakeholders were identified. They imagine a Decision Support System to be the potential treatment in the failure registration problem. In Section 3.1.2 the DSS domain is explored for potential treatments that come in line with the stakeholders needs. The treatment space is narrowed down in Expert Systems (ES) which match with the current needs and the problem characteristics as reported in Section 3.1.3. After exploring the existing diagnostic ES, the decision is taken to design a Failure Mechanism Identification ES entitled as FAME-X. The introduction of the available tools and techniques for developing an ES leads to the adoption of EXSYS Corvid shell as the developing platform for FAME-X. The chapter concludes by reviewing the decision on designing an ES.

3.2 DECISION SUPPORT SYSTEMS

3.2.1 Definition

There is diversity in defining decision support systems or DSS. Different definitions are given from different people. To name a few:

An integrated set of computer tools that allow a decision maker to interact directly with computers to create information useful in making unanticipated semi-structured and unstructured decisions [11].

Information systems featuring an integrated system composed of decision models, database, and decision maker to support decision making [12].

Decision support systems are used for less structured problems...where the art of management is blended with science [13].

Ralph Sprague, in his pioneering work on DSS [14] made a serious attempt to define DSS from a theoretical point of view and in terms of what it means in practice. His compromise, based on observations of many DSS of that era, include these four characteristics:

- They tend to be aimed at the less well structured, underspecified problems that upper managers typically face.
- They attempt to combine the use of models or analytic techniques with traditional data access and retrieval of information
- They specifically focus on features that make them easy to use by non-computer people in an interactive mode.

- They emphasize flexibility and adaptability to accommodate changes in the environment and the decision-making approach of the user.

The definition of DSS we will use in this thesis is as follows:

A decision support system is an information system whose primary purpose is to provide knowledge workers with information on which they can base informed decisions [15].

This definition incorporates the essential elements of the above definitions and others without restricting us to a specific technology, approach, or set of system elements. It is a broad definition that covers all the types of DSS that exist.

3.2.2 DSS types

Steven Alter [16] divided decision support systems into seven levels. The seven DSS types are from the bottom to the top:

1. *File drawer systems* allow immediate access to data.
2. *Data analysis systems* allow manipulation of data using tailored to the task algorithms and settings.
3. *Analysis information systems* provide access to a series of databases and small models.
4. *Accounting models* calculate the consequences of planned actions on the basis of accounting definitions.
5. *Representation models* estimate the consequences of actions on the basis of models that are partially non-definitional.
6. *Optimization systems* provide guidelines for action by generating the optimal solution within a set of constraints.
7. *Suggestion systems* perform inferences leading to a specific suggested decision for a fairly structured task.

Suggestion systems use models to mimic the reasoning process a human expert would use to reach a decision. Then, it suggests the user to make the same decision as the one resulting from the reasoning process. This approach is suitable when human expertise can be coded into a reasonable number of rules. The technology used to construct this type of suggestion systems is called Expert Systems (ES). The exploration of the DSS domain led narrowing down the potential treatments to ES that seem to respect the needs of the stakeholders and match with the problem context. ES are explored in more detail in the next sections.

3.3 EXPERT SYSTEMS (ES)

Expert Systems (ES) are part of a branch of applied artificial intelligence (AI), and were developed by the AI community in the mid-1960s. The basic idea behind ES is simply that expertise, which is the vast body of task-specific knowledge, is transferred from a human to a computer. This knowledge is then stored in the computer and users call upon the computer for specific advice as needed. The computer can make inferences and arrive at a specific

conclusion. Then, like a human consultant, it gives advices and explains, if necessary, the logic behind the advice [17].

3.3.1 ES architecture

The block diagram of an ES or knowledge-based system is shown in Figure 3-1. It consists of the following parts: The database or *knowledge base* or *rule base*, contains the problem solving expertise of the system. It also contains procedures to make logical deductions between symptoms and causes, e.g. mild steel components exposed to water result in corrosion of the steel. In most ES this expertise is expressed as rules in the form of IF (some condition) THEN (some conclusion). Expert system practitioners generally refer to the *antecedent* and the *consequent* of a rule rather than to its condition and conclusion. Rules stated in this form are called *production rules*. The conclusion of a rule may establish other facts that the system will use in subsequent rules, or may lead directly to user output.

An *inference engine* is a computer program that applies the problem-solving knowledge (the rules) in the knowledge base to known facts. An inference engine is a general purpose program that it is not written specifically for a problem or a problem area.

A *graphical user interface (GUI)* is a program that requests information from the user and sends output to the user via a graphical interface. The system asks questions to the user via the GUI. However, it also allows the user to ask questions to the system related to the “how” and “why” it arrived at a specific result.

The *blackboard* is an area in computer storage where the ES stores the facts it has been given about a situation and any other additional information it has derived so far.

Figure 3-1. Typical ES architecture

The *domain expert* and the *knowledge engineer* contribute to the development of the ES but in general do not use it after it has been developed. The knowledge engineer of the ES to be developed here is the author of this thesis. Various domain experts have been consulted. A detailed list can be found in the stakeholder list. The domain expert contributes his or her

expertise in the field of the system but may not know how the ES works. The knowledge engineer is trained both in eliciting information from domain experts and in encoding that knowledge into a knowledge base. Besides the domain experts, the knowledge engineer can seek and elicit knowledge from other knowledge sources such as the literature. Warren Liao et al. [18] in their work present a detailed list of rules that have been generated from a case-based reasoning ES that was fed with 477 failure cases.

An ES is a computer program. It cannot do anything that a conventional computer program could not do. The advantage of an ES is that, in separating the rules in the knowledge base from the inferencing logic that is operated on them, it separates parts of the program that have different characteristics and call for different skills. That separation makes the system easier to change, makes it easier to follow the reasoning process of the system, and lets each human and each part of the system do what he, she, or it does best.

Expert systems are particularly useful in decision support systems at the suggestion system level of the DSS hierarchy. They are generally applied to recurring operational or tactical decisions. Where so applied, they are considered successful if they improve the performance of the typical decision maker, even if this still falls short of an expert's capability.

In Figure 2.1, the arrows represent the data flow among the parts of the ES. The flow starts and ends at the *User interface*. The ES asks the user questions in a predefined sequence in order to have a complete overview of the failure. However, these strategic questions will be defined in a later stage of the design because they depend on the application of the ES and on the knowledge acquisition and organization phase. Moreover, the user will be able to describe the failure under investigation to the ES, by selecting attributes from a drop-down menu. Then the *Inference engine* will try to match the inputs stored in the *Blackboard* with the rules stored in the *Data base*. A final answer will be provided to the user by the GUI.

3.3.2 ES classification

According to their reasoning methodologies ES can be classified in five main categories: ruled-based systems, case-based systems, model based systems, neural networks and fuzzy ESs. These five categories will be discussed in more detail next.

Ruled-based systems

A rule-based ES is defined as one, which contains information obtained from a human expert, and represents that information in the form of conditional rules, such as IF-THEN. The rule can then be used to perform operations on data (find similarities), to infer, in order to reach the appropriate conclusion. These inferences are essentially a computer program that accommodates a methodology for reasoning about the information stored in the rule base or knowledge base, and for formulating conclusions [19].

Case-based systems

Case-Based Reasoning (CBR) solves new problems by adapting previously successful solutions to similar problems [20]. In CBR, descriptions of past experience of human specialists, represented as cases, are stored in a database for later retrieval when the user encounters a new case with similar parameters. The system searches for stored cases with problem

characteristics similar to the new one, finds the closest fit, and applies the solutions of the old case to the new case. Successful solutions are tagged to the new case and both are stored together with the other cases in the knowledge base. Unsuccessful solutions also are appended to the case base along with explanations as to why the solutions did not work [21].

Model-based systems

A model-based system uses mathematical models that depend on knowledge of structures and the behavior of devices or systems. Thus, they work from first principles, e. g. stress equals force over area, rather than that they rely on rules that represent the knowledge of an expert. Model based systems are largely experimental and have been overtaken by CBR. They can be very complex and are best used in linear calculations and programs [22].

Neural Networks

An artificial neural network (ANN) is a model that emulates a biological neural network. This concept is used to implement software simulations for the massively parallel processes that involve processing elements inter- connected in network architecture. The artificial neuron receives inputs that are analogous to the electrochemical impulses that the dendrites of biological neurons receive from other neurons. The output of the artificial neuron corresponds to signals sent out from a biological neuron over its axon. These artificial signals can be changed similarly to the physical changes occurring at neural synapses [19].

Fuzzy ES

Fuzzy ES are developed using the method of fuzzy logic, which deals with uncertainty. This technique, which uses the mathematical theory of fuzzy sets, simulates the process of normal human reasoning by allowing the computer to behave less precisely and logically than conventional computers. This approach is used because decision-making is not always a matter of black and white, true or false; it often involves gray areas and the term “may be”. Accordingly, creative decision-making processes can be characterized as unstructured, playful, contentious, and rambling [19].

In the field of failure analysis, ES can be classified as domain-type failure systems (e. g. bearings, gears, bridges), mechanism-type failure (e. g. corrosion, fatigue, etc.) and generic failure systems [22]. The first two types are specialized and can be used on specific applications or a specific type of industry. Generic ESs cover the most common failure mechanisms that can be found in various components and can be used by different kinds of industries and applications. The latter might have a clear advantage in terms of flexibility, but structuring and coding the knowledge is more complex as there are many factors to be considered.

3.3.3 Failure analysis ES overview

Every problem has a potential treatment. Treatments can be found off-the-shelf or have to be designed from scratch. Before deciding to design a new treatment an investigation of the available treatment for similar problems must be performed. Expert systems have a wide

spectrum of applications. Medical treatment, engineering failure analysis, waste management, financial analysis, agricultural management are only some of them [19]. Here, an overview of the existing Expert Systems for the failure diagnosis domain is offered.

Several ESs are built around standards [22]. They are initially developed for clear commercial reasons of financial gain, and to develop a greater perceived quality in a product or service. Typical examples are *Fatiguewise* and *Crackwise* produced by the Welding Institute (TWI). *Fatiguewise*, as the name suggests, automates fatigue assessment based on British standards. According to the same standards *Crackwise* automates fracture assessment procedures of weld flaws.

Furthermore, ES have been developed for specific mechanical domains. Walton [22] developed an ES to diagnose causes for bearing failure, using a large matrix of bearing failure symptoms and related causes. CRACK [23] is a qualitative ES that diagnoses fatigue and fracture of steel bridges. It is quite successful among others because it uses heuristic, qualitative and quantitative reasoning together with a mode of the physical structure of the bridge. Mayer [24] developed an ES for boiler tube failure mechanism recognition. This expert system has been an inspiration for this work because it is also intended for users with limited knowledge on failure mechanism identification. However, the failure mechanisms treated by this ES are related mainly to boiler tubes, e.g. fire-side corrosion. ESCARTA by Singh and Bains [25] is a similar expert system that was designed to emulate a human expert in boiler tube failure analysis for non-experts. Su *et al.* [26] developed an ES for the tribological failure diagnosis of spur gears that uses rule-based reasoning. Domain specific ESs are quite effective within their domain due to the relatively small amount of knowledge needed for their development. However, their application is limited only to that specific domain.

Another categorization of ES is according to the failure mechanism that they are treating. With a specific failure mechanism being the focus of the system, some are conducting failure analysis and others prediction of failure. ESs were developed with focus to fatigue from companies or by universities [7]–[8]. In the corrosion field, several ESs have been developed and are based on quantitative reasoning. Roberge [29] gives a literature review on corrosion ESs. Similar to domain type, failure mechanism ESs have restricted application to industries and components that face mostly a specific type of failure mechanism.

Generic failure analysis expert systems have also been created. They are dealing with the most common failure mechanisms. FADES, developed by Southampton University [30], used a qualitative approach rather than a quantitative reasoning approach, due to the generic nature of failure problems to be solved. The system uses case-based reasoning (CBR), a methodology which employs knowledge earned by previous experience to solve new problems. Warren Liao [18], [31]–[33] has also developed an ES based on case-based reasoning for failure mechanism identification for mechanical components. The system collects and stores general information about the failed component, for example name, date of failure, etc., and fractographic characteristics of the failure, for example beach marks, shear lips, perforation of the surface, etc. However, CBR provides accurate results only when a large amount of data is available.

Besides CBR, there are other reasoning methodologies used in experts systems. Liao [19] has performed a literature review where expert systems for failure analysis and other applications are classified according to reasoning methodologies. These are rule-based reasoning,

knowledge-based systems, neural networks, fuzzy logic, object-oriented methodology, system architecture development, intelligent agent (IA) systems, modelling, ontology and database methodology. Some of these methodologies are already discussed previously.

3.3.4 Deciding upon the treatment

The treatment is decided to be an Expert System. Failure diagnostics is a subject where expert systems are successful [19] due to the match of the ES logic with the problem characteristics. Failure diagnosis is a well understood and documented domain. The diagnostic process is based on logical steps that do not involve intuition and arbitrary decisions. It is a concrete procedure based on rules and facts; therefore, it matches with the ES logic. The Expert System to be designed is entitled as FAME-X. The title is inspired by the words “failure mechanism” and “expert system”. More design decisions regarding the ES are addressed below.

The ES methodologies previously described were analyzed in order to make a decision about the methodology that will be adopted. A discussion about the selection criteria is essential to make a more concrete justification of the decision. To begin with, the ES proposed in the frame of this project should deal with qualitative input and output. For this reason, ANN and Fuzzy logic are considered as unsuitable for the current ES because, they provide better results when dealing with quantitative data.

Additional constraints that are taken into consideration when deciding upon the treatment are limited the available knowledge and in software engineering and the research orientation of the program in which the current design project is embedded. Also, the research orientation of the group focus on the physics of failure rather than in advanced software engineering. It is believed that a good comprehension of the physics of failure and the interpretation of the tacit knowledge in root cause analysis into a code can result in a useful ES.

Finally, in CBR the system acquires the knowledge by inserting new cases to the system. So, the system’s performance depends on the number of available (relevant) cases, as well as on the algorithm that finds similarities and adapts the old cases to the new. However, cases depend on accurate failure registration. This makes obvious that cases are not available. For the previous reasons, it is decided to adopt the Rule-Based Reasoning (RBR) methodology. The difference is that in RBR, the designer has to formulate and provide the knowledge to the system. The tool’s performance highly depends on this.

3.3.5 Available tools and techniques

A wide variety of software tools is available to support the developer of an expert system [34]. They can be categorized as shown in Figure 3-2.

Custom tools

Custom tools for expert system development are divided in Artificial Intelligence (AI) programming languages and General Purpose (GP) programming languages. A branch of AI languages, known as symbolic languages, enables the development and manipulation of production rules needed for ES. The most common symbolic languages, which are used in the

development of ES are LISP and PROLOG. Both of them are open source. ES can also be developed by GP programming languages, such as Visual Basic, C++ and MatLab. They provide the designer freedom and flexibility. However, the ES has to be built from scratch which demands considerable time and effort from the designer.

Figure 3-2. Expert system development tools

Packages

Package tools offer faster and easier ways to develop ES in comparison to custom tools. Their main advantages are:

- Provide a rich software development environment like structure editors, powerful debugging and tracing facility, multi windows, graphics etc.
- Allow rapid prototyping because of incremental compilers, and automatic version control.
- Defining model, knowledge representation and inference design are built into the tools.
- Help in maintaining the system and historical database.

In general, there are five types of expert system tools [35].

1. *Inductive tools* generate rules from examples. Here a developer feeds in a large number of examples from the machine's information base. The tools use an algorithm to convert the examples into rules and determine the order the system will follow when questioning the user.
2. *Simple rule based tools* use IF-THEN rules to represent knowledge. They are useful for developing expert systems containing fewer than 500 rules. The only problem with these tools is that they lack a high end editing facility for the design of tools.
3. *Structured rule based tools* offer context trees, multiple instantiation, confidence factors, and more powerful editors compared to simple rule based tools. Here IF-THEN rules are arranged into sets. These rule sets act as separate knowledge bases. One set

of rules can inherit the information acquired when other rule sets are examined. These tools are more useful when a large number of rules needs to be processed and rules can be sub-divided into sets.

4. *Hybrid tools* enable complex expert system development. These tools use object oriented programming techniques to represent elements of every problem as objects. Here also a graphical user interface can be provided to users.
5. *Domain specific tools* are specially designed to be used only to develop expert systems for a particular domain. They provide a special development environment and user interface that make it possible to develop an expert system faster. They are also referred as narrow tools.

There are many expert system development tools available in the market. Some of them are Rule Master, MatLab, and SciLab.

Expert System shells

Shells provide user friendly software environment to the knowledge engineer for building an expert system. They assist in designing the knowledge base and user interface while they offer a ready-to-use inference engine and blackboard. They contain all the generic expert system logic required to build an expert system. The main advantages of shells are as follows:

- The level of programming skills needed to produce the finished system is much lower compared to developing a system from scratch using conventional programming methods.
- An expert system development project can be completed faster and cheaper.

Some available commercial ES shells are: EXSYS, Knowledge Pro, XpertRule, KAS, Xi Plus.

3.3.6 ES development tool selection criteria

Rothenberg et al. [36] formulated a list of categories of ES development tool evaluation criteria. The list is addressed to “novices” in developing an ES. According to him, a novice is someone acting as a knowledge engineer who has no experience in AI. Based on these criteria, a decision for the most suitable ES development tool is made. A list with the set of evaluation criteria is presented here:

- Integration and embedding
- Application and domain types
- Problem scale
- Multiple/single user development
- Development environment
- Tool learnability
- Explanation
- Cost
- Future of the tool
- Support

The knowledge engineer with the consultation of the supervisors decided, after careful examination of the available options and their evaluation according to the criteria, to purchase the shell *EXSYS Corvid* for the development of FAME-X. The decision was influenced by the current available programming skills and the timeframe of the project. In addition, EXSYS offers an attractive package which is technically and financially beneficial for the project and the Dynamics Based Maintenance research group in general. The shell can contribute in fast development of the knowledge base and the GUI of the tool. Also, Web access can be achieved without the need of advanced algorithms and techniques.

3.4 TREATMENT REVIEW

In this section, the adopted treatment is reviewed. The review is according to stakeholder needs and requirements. The *expert opinion* research method, which uses expert judgment to validate treatments, was adopted. Experts from the industry and supervisors from the university imagined the implementation of the proposed system in a real environment in order to identify strengths and weaknesses of the treatment. According to their knowledge and experience they imagined how FAME-X can be implemented in the industry and assist non-experts. Their judgement for this conceptual treatment was positive.

By imagining the implementation of the artifact in context several effects are produced. The artifact in this case is FAME-X. The context is a failure investigation in an industrial environment. The first to experience the effects of the implementation are the technicians. Nowadays, they face many problems in reporting a failure due to the lack of knowledge needed to identify the failure mechanisms that act on a material level. The tool will help the user to better understand and analyze the failure, which ultimately will lead to the proper assessment of the failure mechanism. Then, a correct and accurate report will be constructed and the user will have responded fully to his duties, making him confident in tackling failures. Time should be spent on training the user on the ES and collecting information needed for the analysis. Once this experience is gathered, failure analysis will be more effective. Also, each organization has the responsibility to demonstrate the benefits of using the system to their technicians and motivate them to allocate time to consult the ES when applicable.

On operations level, having a more representative report of the causes of the failure helps to provide a more accurate treatment, by reducing the number of exchanged components or redesign the whole system. This way, a repeated appearance of the failure mechanism can be avoided. Furthermore, improving data credibility will lead to more precise maintenance planning.

Currently, simple failures are being overlooked. The failed components are replaced by new ones and only if the failure is more frequent, then experts perform an investigation. In the case of complex failure, a more detailed investigation takes place by specialized people. In both cases, there are high economic and time costs involved. The proposed system can reduce the cost of an investigation by experts and provide solutions in less time.

On an organizational level, structuring failures and symptoms can help create databases with information related to the failure. For example, evidence about date, place, system, component, treatment, technicians, symptoms, causes etc. can be inserted in the database.

The failure history of the company can be archived this way. Preserving such knowledge in an organization is crucial and has great economic advantages.

CHAPTER 4

FAME-X DESIGN PROCEDURE

4.1 INTRODUCTION

A design science project iterates over the activities of designing and investigating. The design cycle can be decomposed into three tasks, namely, problem investigation, treatment design and treatment validation [8]. It is common practice for designers to iterate over the design cycle multiple times during a design project in order to discover whether or not the treatment conforms to stakeholder needs.

The result of the design process – a validated treatment – is implemented to the real world, used and evaluated. This process is the engineering cycle, a larger cycle that incorporates the design cycle (see Figure 4-1). Wieringa [8] states: “design science research projects do not perform the entire engineering cycle but are restricted to the design cycle”. “Transferring new technology to the market may be done after the research project is finished but is not part of the research project”. Hence, for this project the design cycle will be followed. A successful validation of the design can lead to transferring of the treatment to the real world and the initiation of the engineering cycle.

Figure 4-1. Design and engineering cycle.

4.2 THE FAME-X DESIGN CYCLE

The design cycle of the PDEng project is depicted in Figure 4-1. During this initial cycle, followed during the first months of the PDEng project, several iterations over these tasks were performed in order to scope the problem and the treatment sphere. During the *problem investigation* phase, the problem of failure registration in industries was identified, described and explained. These tasks are reflected in Chapter 1. Identification of stakeholders and their needs followed in Chapter 2. The methods employed for investigating the problem are the study of scientific, professional and technical literature. Potential treatments that contribute to stakeholder needs are explored in Chapter 3 which concludes the problem investigation phase. From the various ES methodologies presented, the RBR is selected as the most suitable one.

The next phase in the design cycle is *treatment design*. Before starting the design procedure it is critical to formulate requirements. Needs are transformed into requirements in Chapter 5. The actual design phase starts in Chapter 6. The major steps for designing an ES are then the following:

- Failure mechanism to treat selection: this selection scopes the system and focuses the design on the specific content.
- Knowledge acquisition: the domain knowledge (i.e. failure analysis, RCA, failure mechanisms) is gathered from different sources. The sources are experts in the domain and the available literature. This knowledge is used to describe how the tool will solve the problem.
- Knowledge representation: the acquired knowledge is organized and into a transform in a suitable format for the tool. This format is the IF-THEN rules or production rules which were explained in the previous chapter.
- ES development tool selection: the most suitable tool that respects the requirements of all stakeholders is selected to develop the tool.
- Development of each module and integration: ES are comprised by different parts as shown in the previous chapter. All they have to be developed for the tool to be functional. The development effort strongly depends on the selected ES development tool.

These steps are the guidelines for ES design and have been intergraded with the design cycle of the project. The steps are illustrated in the flowchart in Figure 4-2 and they are described in detail in Chapter 6.

In the last phase of the design cycle, *treatment validation*, the goal is to investigate whether the treatment contributes to stakeholder goals or not. Validation is performed by three different research methods, namely, expert opinion, single-case mechanism experiments and technical action research. The implementation of the methods and the results are reflected in detail in Chapter 8. The methods are used during the design of the ES as an iterative process in order to improve the design. Once the prototype is developed they are used also as final validation. The prototype is presented and its properties are discussed in Chapter 9. It must be noted that the design process finishes in the same manner as it started, i.e. with the problem investigation phase. The conformity of the deliverable with its initial requirements is explored. That is also one of the reason that the process is illustrated as circle and not as straight line. Hence, a prediction regarding the societal embedding and impact of the tool concludes the chapter and the overall design cycle.

Figure 4-2. Flowchart of ES development step.

CHAPTER 5

REQUIREMENT ENGINEERING

5.3 INTRODUCTION

In Chapter 2, the needs for the tool are described and organized in the various levels. In Chapter 5, a formal transformation of the needs into requirements takes place. The requirements of FAME-X are formulated with respect to the levels that the needs are expressed. Then they are verified and validated according to standards. The chapter closes by addressing the way to test their satisfaction.

5.4 REQUIREMENTS

The term “requirement” implies a formal transformation of the needs into an agreed-to obligation for FAME-X to perform some function or possess some quality within specified constraints [10]. However, this work has been supported by several companies and the tool has a generic nature and it is not customized to satisfy the specific needs of any company. The tool rather tries to grasp the principles of failure analysis and facilitate them as an application to be used within an industrial environment. This generic nature of the tool contradicts with requirements which, by nature, are very well defined and structured statements related to very specific needs. However, having no requirements can have many various consequences. There is evidence around us of designs that failed because requirements were not properly organized. Hence, it is critical to attempt requirement formulation for FAME-X project, even when the stakeholders have no direct involvement. This attempt is based on the needs of the stakeholders. In consultation with the supervisors and the INCOSE guidelines the needs are transformed into requirements. A list of the final requirements for FAME-X are presented in Table 5-1. Each requirement is marked by one of the following descriptors:

- MR [Mandatory Requirement] The requirement shall be met; divergence from MR is not permitted.
- KR [Key Requirement] The requirement shall be met, where a customer wishes to propose an alternative a description shall be provided.
- OP [Option] This option shall be offered.

Table 5-1. Requirements for the design.

Number	Level	Status	Description
1.	Stakeholder	MR	A decision support tool for failure assessments shall be delivered within two years.
2.	Stakeholder	MR	A report shall accompany the final deliverable.

3.	Stakeholder	MR	The tool shall be validated and approved by experts.
4.	Stakeholder	OP	A cost analysis shall be carried out that determines the value of the tool.
5.	Stakeholder	MR	Maintenance of the tool shall be carried out by the costumer.
6.	Stakeholder	MR	The content of the tool shall be updated by the costumer.
7.	Stakeholder	KR	The tool shall be debugged before handed over to the costumer.
8.	Stakeholder	OP	Troubleshooting support shall be available for the costumer.
9.	Stakeholder	OP	Training shall be available for the costumer.
10.	Stakeholder	MR	The content of the tool shall be comprehensible by non-experts in failure analysis.
11.	System	MR	The tool shall be accessible by the user via a mobile device.
12.	System	MR	The tool shall treat the following mechanical failure mechanisms: creep, yielding, fatigue, impact, static overload and wear.
13.	System	MR	The failure analysis shall concern components made from metal.
14.	System	MR	The tool shall inform the user about the validity of its suggestions.
15.	System	MR	The tool shall show to the user the decision making path of its suggestions if asked.
16.	System	KR	The tool shall notify the user when it cannot determine the failure mechanism(s).
17.	System	MR	The tool shall interact with the user via a Graphical User Interface (GUI).
18.	System	MR	The tool shall contain explanations of the scientific terminology.
19.	System	MR	The tool shall contain visuals aids (e.g. photos) that will assist the user.
20.	System	OP	The tool shall be accessible simultaneously for maximum 100 users.
21.	System elements	OP	The memory of the tool shall store data accumulated for 5 years.
22.	System elements	OP	The tool shall be compatible with the customer's database.
23.	System elements	KR	The knowledge base shall maintain integrity of the data accessed by concurrent users.

24.	System elements	KR	The knowledge base shall maintain consistency of the data accessed by concurrent users.
25.	System elements	OP	The GUI shall contain text only in font "Calibri" with font size "8".
26.	System elements	MR	The questions asked from the tool shall accept yes/no type answers, if they are applicable.
27.	System elements	MR	The tool shall ask in multiple choice type questions, if yes/no type is not applicable.

5.5 REQUIREMENT VERIFICATION, VALIDATION AND TESTING

The requirement list of the previous paragraph was constructed by following the guidelines of INCOSE. All the rules regarding the clarity, the selection of words used, the avoidance of general expressions (non-ambiguity) and uniformity of language have been respected. Hence, the requirements are verified. In addition, the requirements are validated according to the characteristics of a well-formed requirement as instructed by INCOSE. They communicate the needs of the stakeholders and they restrict the designer to some well-defined obligations.

Defining requirements is considered by many as the initial phase in system's design. However, it has a vital role at every stage of development. The Vee-model demonstrates the influence of requirements at every design step and the necessary tests to check the conformity with requirements. In Figure 5-1 the Vee-model for the decision support tool for failure mechanism identification is illustrated. On the left branch, some of the requirements of the various levels can be seen. On the right branch, there are the tests that should be performed to reassure that all the requirements have been met. The model shows the direct influence of the requirements during the design life cycle of the project.

The Vee-model suggests how and when the requirements should be checked. Some requirements are easy to be tested (e.g. R22, R26), while others demand specific tests to be developed. R10 for example, requires the design of an experiment where the intended users (non-experts) can test the tool. Their feedback can be used to check the conformity with R10.

Figure 5-1. Vee-model of the decision support for failure mechanism identification.

CHAPTER 6

KNOWLEDGE BASE PRELIMINARY DESIGN

6.1 INTRODUCTION

To build any Expert System (ES), knowledge has to be acquired from experts and then transferred in a suitable format to the ES's knowledge base. This is the most challenging part in the creation of an ES and the step where many attempts to build one have failed [22]. Especially, generic ES face this problem due to the variety of failure mechanisms that they contain. Hence, the focus of this project is mostly on the knowledge acquisition and representation phase which is a crucial step for a successful generic ES. In Section 6.1.2, the knowledge acquisition process is discussed. The knowledge representation process is presented in Section 6.1.3. Finally, in Section 6.1.4 format in which this knowledge is stored into the knowledge base.

6.2 KNOWLEDGE ACQUISITION

The knowledge engineer goes through the process of knowledge acquisition to acquire and then store knowledge in the form of facts, rules, case histories and procedures in the knowledge base. The knowledge can be acquired by various sources. In this case, the available sources are listed as follows:

- Exploring the literature (handbooks, standards, etc.)
- Conducting interviews to experts. The experts are the supervisors of this project and people from the industrial environment and the failure analysis field.

The findings from the literature and the interviews with experts are presented in the following subsections.

6.2.1 Failure mechanisms

In Section 1.2 the definition of Failure Mechanism (FM) was given. *Requirement 12* specifies the failure mechanisms that the ES should treat. The author of this thesis researched the literature for the failure mechanisms that satisfy the above requirements. The findings reveal that for the broader categories of FM there is universal nomenclature, for example, wear, fatigue, corrosion. However, for the basic FM different experts use different names. For example, uniform corrosion or uniform attack is used to describe corrosion over the complete surface of a component. It is important for the tool and, by extension, for each customer/industry to establish a fixed nomenclature describing the various basic FM and its broader categories for obvious reasons. Uder [37] presents an extensive taxonomy of mechanical failure mechanisms¹. The taxonomy, due its completeness, was adopted and used as a reference point for this work. In Table 6-1, thirty one basic failure mechanisms and eight broader categories are identified and shown. It is important to note that FM act on a material level. They are related to components and not to systems. For example, when referring to the FM of a bearing assembly, the specific component must be addressed, like the outer ring, inner ring of the bearing, etc.

Table 6-1 Failure mechanism taxonomy [37]

Failure mechanisms	Sub mechanisms	Definitions
Buckling (Deflection based on geometric configuration and load)	Buckling	An increased deflection of a member after a slight change in load as a result of the geometrical configuration and the combination of magnitude and/or point of load.
Corrosion (Material deterioration due to chemical or electrochemical interaction with the environment)	Biological corrosion	The corrosive process resulting from the food ingestion and waste elimination by microorganisms or macro organisms. The waste products of these living organisms act as corrosive media.
	Crevice corrosion	A form of corrosion that occurs within crevices, cracks or joints. Small volume regions of stagnant solution are trapped in contact with the corroding metal.
	Uniform corrosion/ Uniform attack	A common form of corrosion that occurs when the surface of the machine part exposed to the corrosive media is attacked more or less uniformly over its entire surface. The result is a progressive deterioration and dimensional reduction of load-carrying net cross section.
	Galvanic corrosion	Electrochemical corrosion of two dissimilar metals in electrical contact. Current flows through a connecting pool of electrolyte or corrosive medium and leads to corrosion.
	Pitting corrosion	A form of corrosion similar to crevice corrosion leading to the localized development of array of holes or pits that penetrate the metal. The pit can be initiated by a small surface scratch, a defect, or a momentary attack due to a random variation in fluid concentration.
	Intergranular corrosion	A form of attack that occurs when the formation of galvanic cells precipitate corrosion at grain boundaries of copper, chromium, nickel, aluminum, magnesium, and zinc alloys due to the alloy being improperly heat treated or welded.

¹ Uder [37] refers to failure mechanisms as failure modes in his work and defines them as “the physical process or processes that take place or combine to produce a failure effect”. According to the definitions given in Section 1.2, these processes are failure mechanisms. It is common in the engineering world to see terms being used in different ways. However, the definitions given in Section 1.2 are respected throughout this thesis.

	Selective leaching	A form of corrosion in which one element is preferentially removed from an alloy to obtain a metal that is more resistant to the intended environment.
	Erosion corrosion	A form of chemical attack that occurs when abrasive or viscid material continuously flows past a surface thereby baring the material below the surface to the corrosive medium.
	Cavitation corrosion	A form of chemical corrosion caused by differences in vapor pressure. Bubbles and cavities within a fluid collapse adjacent to the pressure vessel walls and cause particles of the surface to be expelled thereby baring the material below the surface to the corrosive medium.
	Fretting corrosion	Occurs when fluctuating temperature fields in the machine part cause load or strain cycling to the point of failure of the machine part.
	Corrosion fatigue	A failure mode in which corrosion and fatigue combine with each process accelerating the other. The corrosive process forms pits and surface discontinuities that act as stress raisers and accelerate fatigue failure. Cyclic loads or strains lead to cracking and flaking of the corrosion layer baring the material below the surface to the corrosive medium.
	Hydrogen damage	Any damage to a metal caused by the presence of hydrogen or the interaction with hydrogen. Such damage includes hydrogen blistering, hydrogen embrittlement, hydrogen attack, and decarburization.
	Stress corrosion	Occurs when the applied stresses on a machine part in a corrosive media generate a field of localized surface cracks, which usually occur along grain boundaries.
Creep (Plastic deformation)	Creep	Occurs when the plastic deformation in a machine member accrues over a period of time under the influence of stress and temperature. The accumulated dimensional changes eventually interfere with the ability of the machine part to satisfactorily perform its intended function.
	Stress rupture	Rupture into two pieces as a result of stress, time, and temperature. The steady-state creep growth period is often short or nonexistent.
Yielding	Yielding	Occurs when the imposed operational loads or motions in a ductile machine member result in plastic (unrecoverable) deformation such that the machine can no longer satisfactorily perform its intended function.
Fatigue (Fluctuating loads or deformation)	High cycle fatigue	The sudden separation of a machine part into two or more pieces occurring when loads or deformations are of such magnitude that more than 10,000 cycles are required to produce failure.
	Impact fatigue	Failure of a machine member by the nucleation and propagation of a fatigue crack that occurs as a result of repetitive impact loading.
	Low cycle fatigue	The sudden separation of a machine part into two or more pieces occurring when loads or deformations are of such magnitude that less than 10,000 cycles are required to produce failure.
	Fretting fatigue	The premature fatigue fracture of a machine part that occurs as a result of conditions that simultaneously produce fretting action and fluctuating loads or strains.
Impact (Impact load of large magnitude)	Impact deformation	The intolerable elastic or plastic deformation that occurs as a result of impact and causes failure.
	Impact fracture	The magnitudes of the stresses and strains that occur as a result of impact are high enough to cause separation into two or more parts.
Static overload	Brittle rupture	Primary interatomic bonds being broken as a result of elastic deformation and the member, which exhibits brittle behavior, separates into two or more pieces. The fracture exhibits a granular, multifaceted surface.
	Ductile rupture	The plastic deformation in a machine part, which exhibits ductile behavior, to the point of the member separating into two pieces. A dull, fibrous fracture surface results from the propagation of internal voids.
Wear (Undesired change in dimension)	Abrasive wear	Occurs when wear particles are removed from the surface by plowing, gouging and cutting action of the asperities of a harder mating surface or by hard particles trapped between the mating surfaces.
	Erosion wear	Occurs when wear particles within a carrier, usually fluid, slide and roll at high velocity against a surface causing loss of material.
	Adhesive wear	A type of wear caused by high local pressure and welding at asperity contact sites followed by motion-induced plastic deformation and rupture of asperity junctions. The result of this form of wear is metal removal or metal transfer.
	Corrosive wear	Occurs when adhesive wear or abrasive wear are combined with conditions that lead to corrosion.

	Surface fatigue wear	An occurrence of wear associated with curved surfaces in rolling or sliding contact. Subsurface cyclic shear stresses produce micro-cracks that propagate to the surface and cause macroscopic particles to be removed by spalling thereby forming wear pits.
	Fretting wear	The presence of fretting action causes a change in the dimensions of mating parts. The changes in 2 dimensions become large enough to interfere with proper design function or large enough to produce geometrical stress concentrations of such magnitude that failure ensues as a result of excessive local stress levels.

6.2.2 Failure analysis and root cause analysis

Root Cause Analysis (RCA) is a problem solving method used for identifying the root causes of faults or problems. When RCA is applied in engineering and maintenance it is called *failure-based RCA* or simply *failure analysis*. In this thesis, the terms *failure analysis* and *root cause analysis* can be used interchangeably. Rausand [38] states that failure in metallic components may be caused by any of the following combination of factors or root causes:

- Design shortcomings
- Material selection
- Overloading and other abuses
- Improper maintenance and repair
- Environmental-material interactions

The failure analyst's goal is to diagnose these factors. It is extremely important that the analyst distinguishes between the mechanisms of the failure and the cause or root cause of the failure. In Chapter 1, it was mentioned that the FM describes how a component failed. The "why" is answered by the root cause. For instance, wear can be a result of wrong material specification (design shortcomings), usage outside of specification limits (overloading and other abuses), poor maintenance – inadequate lubrication (improper maintenance and repair), and so forth. Without knowing the root causes, proper remedial actions cannot be taken, as experts in failure analysis report in their work [39], [40]. This answers to the first of the secondary objectives of the project. Both the failure mechanism and the root cause are needed in order to decide upon proper remedial actions as shown schematically in Figure 6-1 which illustrates an example of the concept. Tinga [41] states the relationship between the applied load and the system capacity (the ability of the system to carry the loads) can be understood when the basic principles of the treated loads and failure mechanisms are known. This knowledge can assist in determining the root causes of many failures.

Figure 6-1. Failure identity example

Many analysts suggest that there should be a systematic way of performing failure analysis (a “methodology”), such as medicals do their autopsies. Vander Voort [42], [43], an expert in failure analysis and senior member of ASM, defines the basic steps of failure analysis as follows.

1. Assemble background data, including:
 - 1.1. History of the part, i.e., processing and service
 - 1.2. Information related to failure, i.e., date, time, place
 - 1.3. Codes, specifications and standards,
2. Perform visual examination of the failure area and adjacent area to determine, photograph, or record:
 - 2.1. Origin of failure
 - 2.2. Presence of stress concentrators
 - 2.3. Presence of temper color or scale of fracture faces
 - 2.4. Orientation and magnitude stresses
 - 2.5. Failure mode and mechanism
 - 2.6. Direction of crack propagation and sequence of failure
3. Perform fractographic examination
4. Perform chemical analysis. Analyze surface corrosion products, deposits, or coatings.
5. Determine mechanical properties, and compare with specification and standards.
6. Perform macroscopic examination.
7. Perform metallographic examination to evaluate microstructural features.
8. Perform micro-hardness tests to measure, case depths, evaluate cold working and determine quality of weldments.
9. Perform high-magnification metallographic examination using electron microscope.
10. Microbe any critical abnormalities, such as inclusions and segregations, which are too small for bulk analysis.
11. Use X-ray techniques to determine:
 - Level of residual stresses

- Identify or determine the relative amount of phases, for example, austenite or retained austenite, martensite in steels.
12. Perform simulation tests to evaluate critical characteristics of the material to determine the degree of embrittlement, or to confirm the method of heat treatment or hardening ability.
 13. Summarize and analyze all pertinent data. Consult with experts when necessary.
 14. Write report with recommendation to prevent similar problems.
 15. Follow up on these recommendations
 16. Preserve the evidence for the benefit of other examiners.

Based on the previous list, it is concluded that failure analysis is an interdisciplinary procedure that requires a vast amount of work and specialized equipment. Only a few engineers are knowledgeable in all of the possible interacting disciplines that can be involved in a given failure; thus, a team effort is essential to fully characterize a failure. However, not all failures require a comprehensive detailed examination. With many types of “routine” failures the procedure can be simple and still be effective.

Expert systems do not tend to replace experts in failure analysis. Besides, based on the previous conclusions, this seems impossible, especially with the simplistic Rule Based Reasoning (RBR) that relies on rules of thumb. Sophisticated artificial intelligence algorithms capable to combine input from different sources, including the analyst, are needed in order to identify the root cause. However, this is not within the scope of this project.

As it was mentioned in previous chapters, the tool will be used by non-experts, mainly technicians or maintainers, who their main task is to repair the failure. This applies certain constraints to the problem. The constraints are cognitive, operational and physical. The users of the tool do not have knowledge over failure analysis techniques and concepts. Also, they do not possess the required equipment, neither have access to in-house laboratories. They can only perform macroscopic visual examination that can be aided by the use of magnifying glass. The cognitive, operational and physical constraints of Table 6-2, being set by the problem, guide the design choices for the tool. Hence, the tool focuses on failure mechanism identification and not on root cause analysis. The latter could be an extension of the current ES and it is discussed in Chapter 10 where future recommendations are given.

Table 6-2: Factors constraining failure analysis by technicians

Cognitive	Procedural	Physical
No background in failure analysis	Limited time	Lack of testing equipment
Educational level	Focus on repairing failures	Lack of laboratories

6.2.3 Failure mechanism identification procedure

Failure mechanism identification is part of failure analysis procedure. Most of the steps described before are also used to identify failure mechanisms. Tanzer [7] highlights the

importance of the information related to the failed part and its background for the investigation. Also, he poses the following key questions used for FM investigation:

- What is the function of the part? How are the characteristics of normal operation?
- How was the part manufactured (e.g. forming, joining, and heat treatment)? What are the targeted properties?
- How was the part installed?
- What is the environment that the part is operated in? Typical environments to examine include operating temperatures, stresses (steady state or slowly rising and cyclic), oxidizing/corrosive environments, and wear environments. What properties were required during service? How were properties expected to change from service exposure?
- What is the maintenance history of the part?
- What are the material characteristics of the part (e.g., composition, strength, hardness, impact, and stress-rupture properties)? What specifications, industry standards, and contracts govern these properties?
- What are the various ways the part could fail?

The list of various FM by which a part can fail can be narrowed down through the application of the following two rules of thumb [7]:

- *The Sherlock Holmes Rule*: When you have eliminated the impossible, whatever remains, however improbable, must be the truth.
- *Occam's Razor*: When two or more explanations exist for a sequence of events, the simple explanation will more likely be the correct one.

The Sherlock Holmes rule is useful in eliminating failure mechanisms, because the observed characteristics will be inconsistent with the characteristics of some failure mechanisms. Consider, for example, the fracture of a high-pressure turbine blade of an aircraft engine [44]. The nimonic alloy turbine blade in Figure 6-2 (a) failed after 5 hours of total operation. Macroscopic fractographic analysis revealed three different fracture zones indicated by the different scales of gray color as shown in figure 6-2 (b). No plastic deformation, corrosion products or wear marks were observed. Hence, creep, corrosion and wear can be eliminated immediately from the list of possible FM. Presence of beach marks is confirmed in Figure 6-2 (c), suggesting fatigue as the FM. Scanning Electron Microscope (SEM) analysis showed progression of crack from the left to right. Striations in zone 2 located in the middle of the blade are illustrated in Figure 6-2 (d). The crack was initiated at the end of zone 1 rather than internally. Based on the low number of cycles and the fractographic evidence, the blade failed by low-cycle fatigue starting from a defective region already having cracks.

Occam's Razor is a useful rule because sometimes two or more explanations are given for the occurred event. However, sometimes it is not possible to verify the correct explanation. Occam's Razor points out the simplest explanation for what is being observed. Both were

taken into consideration during the design procedure of the ES. The users should also use the rules when attempting to identify failure mechanisms.

(a) The fractured turbine blade.

(b) Cross section of the blade showing the three fracture zones.

(c) Beach marks on the fracture surface.

(d) SEM picture showing striations.

Figure 6-2. The failure of a low pressure turbine blade. (a), (b), (c) and (d) show the fractographic characteristics of the blade.

6.2.4 Features for FM identification

Failure mechanism identification highly depends on data collection. In Section 6.2.3, the list of questions for FM investigation provides an overview of the data required for FM identification and damage classification. The list assisted in defining the various features whose identification can lead to a correct classification of damage. In addition, the decision scheme for FM determination by Tinga [3] provided insight on the features that have a critical role in the analysis. These are fractured surface characteristics, the load history of the failed component and the materials. The starting point for the decision scheme is the macroscopic identification of three features cracks or fracture, deformation and surface damage. For each feature there is a list with associated failure mechanisms. Then, by going through a set of questions, all except one mechanism tried to be excluded. The questions investigate the relationship between the above mentioned critical features and the identification of other additional features. This eventually leads to FM determination.

In consultation with the supervisors, the various FM described in Table 6-1 were studied in order to identify the features characterizing each failure mechanism. For example, in components failed by fatigue, typical observations are fracture, beach marks and cyclic load. Similarly, corrosion failures are characterized by a corrosive environment, rust and discoloration.

The vast amount of identified features was filtered and tailored based on the constraining factors described in Table 6-2. It is therefore proposed to the group the remaining features to be grouped in four main categories, namely, *service life conditions*, *materials*, *age* and *post-mortem characteristics*, as presented in Table 6-3. More details on the features in Table 6-3 are given per main category.

Service life conditions concern all features describing what a component might have experienced during its life time, prior to failure. The user must have direct contact and experience with the failed component or available sources to collect the relevant information. The service life conditions can be sub-divided into *load*, *stress*, *environmental conditions*, and *miscellaneous*. The different load types that a component can be subjected are: *static*, *cyclic* and *impact*. The external loads result into the three types of internal stresses, namely, *tension*, *compression* or *shear* stresses. Loads and stresses are caused by the environment that a component is operated in. In this thesis, it is defined that the environment of a component is everything interacting with the component outside of the boundaries that its geometry defines. For instance, the environment of a bearing's inner ring consists of the lubricant and the balls, which both are loading the ring and cause internal compressive stresses. High temperatures caused by friction are also taken into consideration as part of the environment, because they also cause internal stresses and contribute to the deterioration of the material of the inner ring. The environment of a submerged metallic component into the sea is the seawater because its high concentration in dissolved salts (Na^+) and chloride ions (Cl^-) cause chemical reactions known as corrosion. Hence, the environmental conditions have two sub-categories, namely, *contiguity* and *operating temperature* of the component. Contiguity describes everything that bordering with the component. Contact can be established with *gaseous*, *liquid* and *solid* agents or with a combination of them. The user must assess the situation and decide the agent having the highest degree of interaction with the failed component. For instance, a failed jet turbine blade is mounted on the turbine disk which is solid. Gas (air) strikes the blade and turns the shaft. In this case, the user must select as contiguity agent the gas and not the solid because the gas is loading heavily the blade. In Table 6-3, all the features that have to be identified per agent are described. Moreover, the operating temperature is divided into *low*, *room* and *high* temperatures. Miscellaneous contains features related to *surface quality*, *slenderness ratio* and *geometry prone to stress concentration*. The user is called to identify these features on the examined component.

Age of the component refers to the time interval of a component from a good-as-new state until failure. This means that the component can be brand new, or overhauled and restored to as-good-as-new state before it fails completely. The three age classes are: *new*, *medium* and *old*. In order to classify the component in one of the three classes, the user must collect information about the typical or expected lifetime of the component, its current life and its maintenance history.

Table 6-3: Failure Characteristics. The indentation in the subdivision column denotes the different subdivision levels.

Main Category	Subdivision				Options						
Service life conditions	Load				Static	Cyclic	Impact				
	Stress				Tension	Compression	Shear				
	Environmental conditions										
		Contiguity									
			Gas				Stagnant	Regular flow	Turbulent flow		
			Liquid								
				Water							
				Movement				Stagnant	Regular flow	Turbulent flow	
				Composition				Pure	Sea water	Bio-Contaminated	Inclusions contaminated
			Bio-products				Fungus /mold	Soil/mud			
			Solid								
			Relative movement				Static	Moving	vibrating		
			Material properties of the component in contact								
				The component is harder				Yes	No		
				Galvanic series position				Higher	Lower		
				Lubrication				Poor	Good		
		Third particle presence				Yes	No				
	Operating temperature				Low	Room Temp.	High				
	Big slenderness ratio				Yes	No					
	Geometry prone to stress concentration				Yes	No					
	Surface quality				Low	High					
Age	Time to service				New	Medium	Old				
Post-mortem characteristics	General										
		Plastic deformation				Yes	No				
		Rust				Localized	Uniform				
	Fracture										
		Fracture characteristics				Ratchet marks	Beach marks	Chevron marks			
						Thick shear lips 45 degrees		Jagged lighting path			
		Fracture description				Woody texture	Rocky candy texture	Caving around fracture	Perforated		
	No fracture				Blistering	Grooves, gullies	Holes				
					Pitting, spalling, gouging	Cracks	Discoloration	Dented			
	Materials	Category				Steel	Tool steel	Cast iron	Stainless steel		
Aluminum alloys						Super alloys					
Type				Brittle	Ductile						

Post-mortem characteristics refer to features describing the component after failure occurs. The user should investigate macroscopically, with naked eye or by the aid of magnifying glass, the failed component. The analysis will lead to identification of features belonging to one more of the three classes, namely, *general*, *fracture* and *no-fracture* features. *Plastic deformation* and *rust* observations belong to the general class. Failures with fracture can be classified in two classes which provide a general description to fracture and contain more specific fractographic characteristics identifiable with closer examination. Indicatively, some of them are beach marks, ratchet marks, chevron marks and shear lips.

In the **materials** category, metals are subdivided to *steels*, *tool steels*, *cast iron*, *stainless steel*, *super alloys* and *aluminum alloys* [45]. Note that according to Requirement 13, the ES will treat only metals. These metals exhibit different properties and are used in different applications. Tool steels, cast iron and super alloys have high strength. Stainless steel and aluminum alloys perform well in corrosive environments while normal steels, if not protected, corrode easily. The user should investigate the type of material used to make the failed component.

6.3 KNOWLEDGE REPRESENTATION

In Section 6.2, the required knowledge for failure mechanism identification was presented. The various failure mechanisms were defined and the questions leading to them were imposed. This resulted to establishing the failure features which are the evidence that, eventually, will contribute to failure mechanism diagnosis. The transfer of failure knowledge to the Expert System requires the knowledge to be organized and represented by *production rules*. In this Section, the failure knowledge is organized in a suitable format that facilitates rule extraction. Then, the rules used for the ES are presented.

6.3.1 Failure matrix

In a more generic Expert System (ES), the organization of the failure knowledge is more complex as there are many factors to be considered [22]. In Dolan [46], a matrix of failure mechanisms (e.g. brittle and ductile fracture, fatigue, corrosion, creep, embrittlement) against operating conditions and mechanical properties (e.g. loading more, stress type, operating temperature, material type) is shown. When a failure mechanism has a relationship with one of the attributes an "X" is noted in the corresponding shell. Tinga [3] in the previously introduced decision scheme for FM determination poses diagnostic questions and labels their content according to the relevance with the associated FM. There are questions with required conditions for the FM to occur, others that confirm the presence of a FM and some that exclude the presence of the associated FM. According to the answers FM are confirmed, excluded and remain still active in the analysis. In this way only one potential FM remains. Dolan's and Tinga's work have been an inspiration and the basis for the FAME-X. This work presents a large matrix, containing every most common failure mechanism and a plethora of failure features with more refined relationships

The study of the failure mechanisms of Table 6-1 resulted to the attributes of Table 6-3. For some attributes the connection to the failure mechanisms is obvious, but for others more detailed investigation of the literature and consultation with experts is required in order to discover their correlation. For instance, let us assume, Low Cycle Fatigue (LCF) is responsible for the failure of one component. If the investigation reveals that the component was loaded cyclically and beach marks were presence, the evidence confirm the assumption. If only shear lips are observed, then the observation suggests LCF but the assumption cannot be confirmed. Finally, if the component is loaded statically, then the assumption is rejected for obvious reasons.

Certain failure features are fundamental characteristics of some failure mechanisms and directly point towards them. Most of the time they characterize the whole broad category of failure mechanisms. For example, cyclic load is necessary to develop fatigue as high operating temperatures are necessary for creep. Other failure features help to distinguish between the failure mechanisms of the same family. For example, corrosive wear can be excluded from the wear mechanisms when rust is not present or the component is not exposed in a corrosive environment. This example also demonstrate the use of the Sherlock Holms rule in the analysis.

This reasoning leads to the introduction of a scalar notation system to denote the relationship between FM and failure features as shown in Table 6-4. The symbols are used to define the relationship between each failure mechanism and each failure feature. A failure matrix containing 31 failure mechanisms and more than 60 failure features is created. Due to the size of the matrix, a small sample is only presented here for practical reasons in Table 6-5. The whole matrix can be found in Appendix B.

Table 6-4: Scalar notation system denoting the relationship between FM and failure attributes.

Notation	Explanation
	Necessary characteristic for the specific failure mechanism of the corrosion family.
	Necessary characteristic for the specific failure mechanism of the fatigue family.
3X	Necessary presence of the feature for the whole family of failure mechanism.
XX	Presence of this symbol strongly suggests the failure mechanism.
X	Presence of this symbol suggests the failure mechanism.
I	Presence of this symbol means the feature does not contribute to the failure mechanism.
O	Presence of this symbol eliminates the failure mechanism.

Table 6-5: Failure matrix

Failure Mechanisms	Failure features																			
	Load			Stress			Environmental conditions													
							Operating temperature			Contiguity										
										Gaseous	Liquid									
											Bio-product s	Water								
												Movement				Composition				
												Stag-nant	Regular	Turbulent	Pure	Sea water	Contaminated	Inclusions		
O ₂ , SO ₂ , CO ₂	Fungus/mold	Soil/mold	Crevice	Flat surface																
	Static	Cyclic	Impact	Tension	Compression	Shear	Low	Room	High	O ₂ , SO ₂ , CO ₂	Fungus/mold	Soil/mold	Crevice	Flat surface	Regular	Turbulent	Pure	Sea water	Contaminated	Inclusions
Biolo-gical corrosion	I	I	I	I	I	I	I	I	X	3x	3x	3x	I	xx	I	O	O	3x	xx	I
Crevice corrosion	I	I	I	I	I	I	I	I	X	3x	I	3x	3x	O	xx	O	O	O	I	xx
Uniform corrosion	I	I	I	I	I	I	I	I	X	3x	I	I	I	xx	X	X	O	3x	I	I
Corrosion fatigue	O	3x	I	xx	X	X	I	I	X	3x	I	I	I	X	X	X	O	3x	I	I
Hydrogen damage	I	I	I	X	X	I	I	I	X	X	I	I	I	X	I	I	O	X	I	I
High cycle fatigue	O	3x	I	xx	I	X	I	I	X	I	I	I	I	I	I	I	I	I	I	I
Low cycle fatigue	O	3x	I	xx	I	X	I	I	X	I	I	I	I	I	I	I	I	I	I	I

6.3.2 Production rules

Production rules represent knowledge about how to solve any problem within the class of problems with which an expert system deals [15]. It is the format in which the knowledge is inserted in the knowledge base. The rules are expressed in the form: IF (some condition) THEN (some conclusion). For example, "IF there is a cyclic load, AND the component is in a corrosive environment, THEN the failure mechanism is corrosion fatigue". ES practitioners refer to the *antecedent* and the *consequent* of a rule instead of its condition and its conclusion. The conclusion of a rule may establish other facts that the system will use in subsequent rules, or may lead directly to user output. The generated rules are stored in the knowledge base.

In the ES proposed here, production rules are used in two different ways. At first, the rules concern features that are able to determine directly one or more families that the failure mechanism belongs to, e.g. "IF beach marks THEN fatigue". This means that if beach marks are observed, then the failure mechanism belongs to the fatigue family. These features will be called from now on *top level factors*. In this case, the consequent is a *failure mechanism family*. After a first broad classification of the FM according to the top level factors, the *second level factors* are to be identified. The second level factors contribute to the identification of the *basic FM* which belong to a specific FM family. These factors are identified during a second

stage of the analysis. For example, if fatigue is diagnosed in the first stage, then the tool will try to find the second level factors that will lead it to distinguish among the different types of fatigue involved. This second stage contains production rules that assign a score to a specific *basic FM* which takes the role of the consequent this time. This has the following form:

```
IF      static load
THEN    LCF = 0
        Brittle rupture = 20
```

This means that if the component is statically loaded, LCF is eliminated and brittle rupture is strongly suggested. Later, in Chapter 7 more details about the use of the scores follows. The process of investigating the top and second level factors previously described is presented schematically in Figure 6-3. The process indicates that the tool continues the identification of second level factors for all the FM families that have been identified. The process finishes when the user believes that the results are satisfactory. Otherwise, the analysis is repeated with and the user has to collect more data. The structure of the knowledge base of the tool is build according to this process. Also, the analysis and the results are presented to the user in the same manner.

Figure 6-3. Production rules and levels of features

CHAPTER 7

FAME-X DETAILED DESIGN

7.1 INTRODUCTION

The knowledge for failure mechanisms identification that has to be inserted in the knowledge base has been collected discussed and organized in the Chapter 6. Here, the next step in the ES design procedure is presented. Chapter 7 describes the tools and the methods by which the problem solving knowledge is intergraded to the ES. It concludes by presenting the architecture of FAME-X.

7.2 DESIGNING FAME-X WITH EXSYS CORVID

7.2.1 Introduction to EXSYS Corvid

EXSYS Inc. is an American company that produces software tools for the development of expert systems. Their products, such as Corvid, offer the possibility to convert complex decision-making processes into an interactive application that can easily be incorporated into a web page. EXSYS tools traditionally practiced Rule-Based Reasoning (RBR). Corvid, though, is based on both a Microsoft's Visual Basic (VB) model and RBR. It provides an object-oriented structure that makes it easy to build systems using methods and properties of variables, while not requiring the developers to change the way they think and describe their decision-making steps and logic.

Corvid introduced a new concept in managing decision-making process, called *Logic Blocks* (LB). LB are a superset of tree logic diagrams and rules that have a related function. This allows the logic to be organized into blocks that behave as objects. LB can be executed in *forward chaining mode* or *backward chaining mode*. The first mode runs the rules in the order that they have been created. The latter mode, executes only the rules needed for a specific decision each time. FAME-X is based on backward chaining. More details on how the inference engine uses backward chaining can be found in Section 7.2.4. Mode selection and execution of LB is applied through *Command Blocks* (CB). CB, generally, control how a system operates, what actions to take and in what order to perform actions. They are the skeleton of an ES. Hence, most ES have only one CB.

Corvid allows the deployment of interactive ES on websites and as standalone applications in a non-web environment. The user has to select between *applet* or *servlet runtime* development. The first uses Java that allows robust interface design options in combination with speed. Servlet runtime is an alternative method of Web based delivery that allows Corvid systems to be run via a server-side Java servlet with all user interaction through HTML screens and forms.

7.2.2 Variables

To facilitate the creation of IF-THEN rules, Corvid uses variables. There are 7 types of variables and all can be created and edited at the *Variables* window. However, only two of them are suitable for the purposes of this work. These are the *Static list* and *Confidence* variables.

Static list variables are multiple choice lists with the values defined during the development of the system. For every feature to be identified, there is one static variable. Basically, these are all features belonging to the *Categories* column of Table 6-3. The static variables can take certain values. These value are also specified in Table 6-3 under the heading *Options*. Examples of static list variables are shown in Table 7-1.

Table 7-1 Examples of static list variables

Variable	Values
Load	Static, cyclic, impact
Stress	Tension, compression, shear
Age	New, medium, old
Stress concentration geometry	Yes, no

In Figure 7-1, the static list variable window is illustrated. All variables have a prompt that describes in detail what the variable means. This is used both for asking the user to input a value for the variable and when results are displayed. In the value space highlighted with red, the text entered describes the value. The value text will be appended to the prompt for the variable to build a statement. The same text will also be presented to the user if the system needs to ask for the value for the variable.

Figure 7-1. Variables window indicating the static variables. Highlighted with red is the value field where the name of the value can be defined.

FM diagnosis is accompanied by a confidence value to demonstrate the validity of the suggestion with respect to the input provided by the user. The value basically provides an indication to the user of the trustworthiness of the suggestion. All basic failure mechanisms are represented by confidence variables. The values contributing to the confidence levels are defined according to the scalar notation system introduced in Table 7-2. In order to diagnose a specific FM, the tool requires some specific features to be identified and to have them reported. If all these features are reported, then the confidence will be maximum (confidence will then equal the value 1). If less features are reported, then the confidence will be proportionally lower. The confidence value thus represents which fraction of the potential amount of evidence for a specific FM is actually encountered in the case at hand. The tool ranks the FM according to their confidence value and suggests the FM with the highest confidence as having the most support. Confidence should not be confused with probability, as the latter would suggest how probable (in a quantitative sense) the occurrence of a certain failure mechanism would be, i.e. how large the risk for that FM would be. That information can however not be derived from the features that the tool is aiming at. If all confidence values are zero, the tool will not be able to suggest any FM, as apparently no support or prove for any specific FM has been found or reported. The example of the fractured Nimonic alloy

turbine blade of Section 6.2.3 is adopted to make the use of confidence variables more understandable.

Table 7-2. Scalar notation system denoting the relationship between FM and failure attributes. The table is the same as Table 6-4. It is repeated here to assist the user in reading and comprehending the content of this section.

Notation	Explanation
	Necessary characteristic for the specific failure mechanism of the corrosion family.
	Necessary characteristic for the specific failure mechanism of the fatigue family.
3X	Necessary presence of the feature for the whole family of failure mechanism.
XX	Presence of this symbol strongly suggests the failure mechanism.
X	Presence of this symbol suggests the failure mechanism.
I	Presence of this symbol means the feature does not contribute to the failure mechanism.
O	Presence of this symbol eliminates the failure mechanism.

The identified beach marks belong to the top level factors and suggest that the failure is due to fatigue. A distinction between the different basic mechanisms of fatigue is needed. Age is a static list variable. High Cycle Fatigue (HCF), LCF, Impact fatigue and fretting fatigue are defined as confidence variables. The ES will ask the user to specify the age of the component. With 5 hours of operation, the component is considered as new. When the user selects *New* as answer, the following rule will be activated in the ES:

IF Age = New

THEN LCF = 0 (because the notation is **O**)

HCF = 50 (because the notation is **3X**)

Impact fatigue = 10 (because the notation is **X**)

Fretting fatigue = 0 (because the notation is **O**)

Based only on this single feature, LCF is the most supported failure mechanism by the tool because it has the highest confidence value.

EXSYS Corvid contains various formulas that can be used to calculate confidence. Here, the *Sum* method is used where the values are added together. Positive values increase the confidence of an FM, and zero values eliminate the FM; negative values do not exist. The confidence of a failure mechanism is the sum of the values, which then reflects the total contribution (i.e. support) of the identified features to the specific failure mechanism. Let C_i denote the confidence of the i^{th} failure mechanism, with $i = 1, 2, \dots, 35$. Let $r_{ij} \in [0, 10, 20, 50]$ denote the effect of an identified feature j to the specific failure mechanism i . The possible values of r_{ij} are defined based on the Table 7-2. The confidence of each FM is then expressed by the following formula:

$$C_i = \sum_{j=1}^n r_{ji} \quad (1)$$

where n depends on the number of features that have an effect on the failure mechanism i . Basically, the values [0,10,20,50] represent numerically the notation system. They are a convention adopted in this work to facilitate the calculation of the confidence. In principal these values can be substituted by any values $[x_a, x_b, x_c, x_d]$ as long as $x_a < x_b < x_c < x_d$. Still FAME-X would suggest the same FM as the most dominant. The confidence value would also remain the same because it is being normalized.

This is because the number of features, and thus the number of contributions r_{ij} to the total confidence, varies across the FM. Hence, normalization is needed to facilitate the comparison and, eventually, the identification of the most supported FM. The normalization is performed by dividing the confidence scored during investigation by the maximum confidence of each failure mechanism. The maximum confidence for each FM is calculated based on the notation of Table 7-2 and the corresponding values can be found in the failure matrix in the Appendix B under the column "Max confidence". Normalization takes place in the Command blocks.

Features contribute to all failure mechanisms, except for those where the notation symbol "I" is placed in the respective cell in the failure matrix. It is important to note that when a feature noted by "O" for a specific FM is identified, then this FM must be excluded from the suggestions. In order to achieve that the confidence of this FM is set to zero permanently, even though that other characteristics of the FM might be identified. For instance, if the component is loaded statically, then the confidence values of all fatigue mechanisms are set to zero immediately. The value then locks and cannot be altered anymore. This helps to eliminate FM quickly and to keep only those that are rational for a given problem. The *lock value* option is offered in the confidence tab which is illustrated in Figure 7-2. The inspiration comes from the Sherlock Holms rule that it is introduced in Chapter 6.

Figure 7-2. Variables window in Corvid indicating the confidence tab in the red square. The arrow shows the lock value option.

7.2.3 Logic blocks

The knowledge base contains the problem solving logic of the ES. Here, the procedure of designing the knowledge base and loading the logic of failure mechanism identification as described previously is explained.

In Corvid, the knowledge base is constituted by logic blocks (LB). These are constituted by production rules or If-Then rules that can stand individually or can be organized in tree diagrams. Blocks are created and edited in the Corvid logic block window. The failure mechanism identification expert system uses eight blocks. The first block is dedicated to identifying the first level factors as described in Chapter 6. In this level, the system will ask the users questions related to the features of the failure matrix (see Appendix B) indicated by a blue color. The remaining seven² blocks are dedicated to each of the failure mechanism families and to the collection of second level factors. These factors are related to features that

² There are eight failure mechanism families, but for *Yielding* there are no features to identify in the second level factors. Hence, the number of logic blocks is seven.

aim to distinguish between the different basic FM that belong to the same FM family. The LB at this level are: buckling, corrosion, creep, fatigue, wear, static overload and impact.

The order of the production rules for a given logic block defines also the order of the questions asked to the user. For example, if the system examines fatigue, then the tool activates the fatigue logic block and executes the lines of code (i.e. production rules) in the order that they are written. This order respects the Sherlock Holmes rule which is introduced in Chapter 6. According to it, the rules are positioned with respect to their capability to eliminate failure mechanisms. This capability is defined by the number of "O" (see notation Table 7-2) per feature (e.g. load, materials). This estimation was performed by studying the failure matrix. The features and consequently the rules are ranked according to this capability. Several improbable, based on the input, FM could be eliminated quickly which the system would not examine them further. This technique accelerates the diagnostic process because it minimizes the number of questions asked to the user. The disadvantage is that the questions are not thematically coherent which could create confusions.

In Figure 7-3, the logic block for *Impact* in the graphical interphase of Corvid is illustrated. The green and grey symbols denote antecedents of the rules composed by static variables and the yellow symbols represent the consequents composed by confidence variables. At the lower part of the window, there is a panel with different options used for editing the rules. In Figure 7-4, the rule view window of Corvid is presented. This is a handy tool that assists the developer to have a quick view of a production rule that includes the prompt and the value given by the user.

Figure 7-3. Logic block Impact on EXSYS Corvid

Figure 7-4. Rule view window of EXSYS Corvid.

7.2.4 Command blocks

The logic blocks in a system have the detailed logic of how to make a decision, but these must be invoked from a command block. Most of the fundamental command blocks control what variables the system will try to derive values for, and what logic blocks will be used to do that. Command blocks therefore control the procedural flow of the system including how the system chains, executes the logic blocks, loops, and displays results. They are the only way to interfere with and control the inference engine.

Command blocks can be simple with a single command that starts backward chaining on all confidence variables; up to more complex systems that involve “while” and “for” loops and several other commands. These modules assist in developing the algorithm for failure mechanism identification. The algorithm is based on the process explained in Section 6.3.2 and illustrated in Figure 6-3. A flowchart of the algorithm is presented in Figure 7-5 and its steps are explained here:

1. Start of the algorithm.
2. Initialize variables.
3. Derive all the FM families FMF_i present to the failure (identify top level factors).
4. Present to the user the identified FM families present to the failure.
5. Derive the basic FM BFM_{ij} for each identified FM family (identify second level factors).

6. Calculate BFM_{ij} confidence.
7. Normalize BFM_{ij} confidence.
8. Present to the user the basic FM identified in descending confidence order.

The above algorithm, at first, identifies the failure mechanism families present to the failure asking to the user to identify the top level factors. This done by using binary confidence values which are multiplied and provide a binary total confidence. *Multiplication* is another option offered by Corvid that facilitates the calculation of the binary confidence. It is described by the following expression:

$$C_i = \prod_{j=1}^n r_{ij} \quad (2)$$

where C_i is the overall binary confidence, $r_{ij} \in [0\ 1]$ is the effect of an identified feature j to the specific failure mechanism i and n is the number of the features which depends on each basic FM. When a zero is assigned at any point then the overall confidence will become zero because it is calculated by multiplication. Once the basic FM are known and presented to the user, then the basic FM are investigated separately by asking to the user to identify the second level factors. The confidence of the basic FM is calculated based on the *Sum* function and equation (1). Then, confidence is normalized as explained in Section 7.2.2. Finally, the results accompanied with a confidence number are presented to the user.

The algorithm is realized in a command block in the Corvid command block window which is illustrated in Figure 7-6. The “SET” commands in the beginning are used to initialize the values of some static list variables. Then “DERIVE” commands the system to collect values for the confidence values representing the various FM families in backward chaining mode.

Backward chaining is the way that the inference engine combines the rules in order to calculate confidence variables. It is a goal driven solving approach. Defining the confidence value of a specific variable is a new goal each time for the inference engine. The inference engine can determine what it needs to meet a particular goal including determining when the goal is met or that a goal cannot be met. To accomplish the goal, the engine in backward chaining mode searches the knowledge base to find the rules that can assign confidence values to this variable. In many cases, these rules are chained with other rules that contain different variables that require values. In this case, the engine sets a new goal to calculate the needed values and assign them to the variables. This procedure is run iteratively until all confidence variables that the command block requests in order to solve the problem are set. For example, the command “DERIVE [HCF]” sets as goal to estimate the confidence for HCF and only the rules that contribute to HCF are executed. This means that only a fraction of the questions will be asked to the user.

Figure 7-5. Flow chart for the failure mechanism identification process.

Figure 7-6. Command block window in Corvid showing how the flowchart translated into a code.

7.2.5 Graphical User Interface (GUI)

The Corvid runtime program interacts with the users by displaying the system title, asking questions, and displaying messages or results. Corvid provides a set of interface commands that allow text and graphics to be formatted and included in these displays.

Most of the parameters for how questions are asked are set in the window for editing questions illustrated in Figure 7-7. This dialog defines controls such as checkboxes, radio buttons and others. For the ES, the radio button and check box options are used depending on the type of question. A radio button allows only one option to be selected each time, while a check box allows the selection of multiple options.

Corvid also allows information or graphics to be added and displayed before, during, or after a question is asked. This option is exploited extensively in order to make the content of the questions comprehensible for the user. In Figure 7-8, explanations of scientific terms “static” and “cyclic” with text are introduced to facilitate value selection. A different way to explain terminology than verbal is optical. Figure 7-9 shown that the terms “broken” and “severely cracked” are clarified by the use of images. Asking question can be also done directly with the use of images as shown in Figure 7-10.

The GUI design is realized this way in order to satisfy the Requirement (R10) which demands the comprehensibility of FAME-X by non-experts in failure analysis. To that respect, the design

choices are made to enhance the readability, comprehensibility and user-friendliness of the FAME-X. This is believed to be achieved by using visual aids, text explanations of the scientific terminology, eliminating free text input and guiding the user by constraining the possible answers with the format of the questions (i.e. radio buttons).

The figure shows a 'Question editing window' with several tabs: Prompt, To Be, Options, Link, Ask With, Also Ask, and Servlet. The 'Ask With' tab is selected. Inside this tab, there are two main sections: 'Use' and 'Arrange'. The 'Use' section contains radio buttons for 'Radio Button', 'Drop Down', 'Checkbox' (which is selected), 'List', 'Image Map', and 'Button', along with an 'Edit Map' button. The 'Arrange' section contains radio buttons for 'Same as Prompt', 'One per line' (which is selected), 'N/line, N= []', and 'All on one line'. To the right of these sections are checkboxes for 'Use Image Files' (with sub-options 'JPG' and 'GIF') and 'Last value clears all others', along with a 'Preview' button. Below these sections is an 'Other Graphics' section with radio buttons for 'Before' (selected) and 'After', and a text input field with an 'Edit' button. At the bottom, there are two text input fields labeled 'Prompt Format' and 'Value Format', each with an 'Edit' button.

Figure 7-7. Question editing window in Corvid.

The figure shows a GUI window titled 'FAME-X Time to service'. It contains a note: 'Note: In order to classify the service life of the component into New, Medium, Old the user must be assured that the component is used as intended by the manufacturer. If the component is not used properly, please select the corresponding option.' Below this is a section 'Characterize the failed component according to its life time to one the following categories:' with radio buttons for 'New', 'Medium', 'Old', 'Not used as intended by the manufacturer', and 'Not known'. A 'Clarifications:' section follows, explaining the component's life cycle. At the bottom, there are navigation buttons: 'Next', 'Restart analysis', 'Back', and 'Exits'.

Figure 7-8. Explanation of terminology with the use of text in the GUI of the ES.

Is the component broken or severely cracked?

☐ Yes

☐ No

Here are a few examples of broken and cracked components

Broken

Cracked

Figure 7-9. Explanation of terminology with the use of images in the GUI of the ES.

Post-mortem characteristics

After examining the component for corrosion products (rust), classify the findings in one of the following categories:

☐ Localized corrosion products on the part

☐ Extended corrosion products on the part

☐ No corrosion products are visible

Clarifications:

If the rust is concentrated in specific spots, then it is localized. Otherwise the rust is extended over the whole component or the area exposed to corrosive environment. The following examples helps to distinguish between the two types.

Localized corrosion

General corrosion

Figure 7-10. Question being asked by the use of images in the GUI of the ES.

7.2.6 System architecture

FAME-X is developed on the platform EXSYS Corvid which is an Expert System (ES) shell. Shells structure systems in a specific way that assists the knowledge engineer to create, with the use of logic blocks, productions rules (IF-THEN) and to connect them together by creating logic trees. The knowledge base stores the rules. Moreover, EXSYS Corvid facilitates Graphical User Interface (GUI) development. The operational flow of the system is defined by an algorithm designed in Command blocks. The smooth operation and integration of all the different parts (i.e. knowledge base, GUI, inference engine) is controlled by EXSYS Corvid with limited access to the developer. However, full control is given on the problem solving methodology and appearance of the tool.

A schematic view of the architecture of FAME-X and the interconnections of the different parts is illustrated in Figure 7-11. The figure shows where the action takes place and what action takes place. The knowledge base contains the failure mechanism identification methodology. The tools to capture the methodology within the expert system are the variables block, the logic blocks and the command block. The GUI, which is controlled by the algorithm designed in the command block, facilitates the interaction with the user. It shows screens containing titles, questions and results. Also, it collects the input of the user which is stored in blackboard. EXSYS Corvid has its own inference engine which, in the case of FAME-X, operates based on backward chaining to calculate the confidence variables. The inference engine calculates the confidence values that the command block requests based on the input of the user by communicating with the blackboard. Once, the tool has estimated all confidence variables, then it displays their values in the form of results via the GUI to the user.

Figure 7-11. Schematic view of the architecture of FAME-X showing what actions take place at which location.

CHAPTER 8

FAME-X VALIDATION

8.1 INTRODUCTION

The validation of FAME-X aims to show that it would contribute to stakeholder goals when implemented in the industrial environment and used by its intended users. The problem of validation is that no real world implementation is available to investigate whether the tool contributes to stakeholders goals. Implementation is part of the engineering cycle and cannot be fulfilled in this project as discussed in Chapter 4. To overcome this problem, Wieringa [8] suggests to build validation models of the artifact in context, i.e. of the FAME-X investigating a failure in an industrial environment. Based on these models, a design theory is developed, which is a theory of the properties of the artifact and its interaction with the problem context. Then, this theory can be used to predict the effects of an implemented FAME-X in the real world. It is important to note that with the word “model” Wieringa means an analogous model which is defined as: “an entity that represents entities of interest, called its targets, in such a way that questions about the targets can be answered by studying the model”. “Model” is used in the same way in this thesis. For example, an electrical network is used as a model to study a network of water pipes and an animal is used as a natural model of human beings to study the effect of drugs.

A validation model consists of the artifact (i.e. FAME-X) interacting with the problem context (i.e. failure case study) as shown in Figure 8-1. The target of the validation model is the FAME-X, in a final version suitable for industrial usage, investigating an industrial failure. The model is created by similarity to its targets, meaning that the model is trying to be as close as possible to reality.

Validation models are studied by research methods. Three different research methods have been adopted from Wieringa [8] to validate FAME-X in different stages of the project. These are *Expert opinion*, *Single-case mechanism experiments* and *Technical action research*.

Figure 8-1. A validation model of the FAME-X prototype representing its target by similarity. It is used to answer how FAME-X would deal with an industrial failure when being operated in an industrial environment.

The expert opinion and the single-case mechanism experiment methods are used as an iterative process to improve parts of the design as well as a validation of the final design. The two methods pointed out different flaws of FAME-X to be corrected. The iterative process continued until the tool was able to identify the correct FM. On the other hand, the technical action research method is used only for the validation of the prototype tool. The results of the different methods are presented and discussed below.

8.2 EXPERT OPINION

Expert opinion uses expert judgment to validate treatments. It is the simplest method to validate the tool and it has been used in different design stages throughout the project. Experts from the industry and supervisors from the university imagined the implementation of FAME-X in a real environment in order to identify strengths and weaknesses of the treatment. This was firstly performed at the stage where the decision to develop an Expert System (ES) based on Rule Based Reasoning (RBR) was taken. It continued during the development of FAME-X to validate the production rules of the tool. At last, it is used at the final validation stage, where experts expressed their opinion for the tool.

The method aims to validate the design with respect to the stakeholder requirements and partially the system level requirements. Some of them are the capability of the tool to assess failures, the comprehensibility by non-experts, the accessibility of the tool and the failure mechanisms treated. The results of the experiments can be generalized and adopted as the final opinion of the stakeholders for FAME-X.

According to their knowledge and experience they envisioned how the ES can be used by non-experts to guide them in failure mechanism identification. This attempt revealed that the tool could help the non-expert user to better understand and analyze the failure, which ultimately would lead to the proper assessment of the failure mechanism. Then, a correct and accurate report would be constructed and the user would have responded fully to his duties, making him confident in tackling failures. The stakeholders suggested that time should be spent on training the user on the ES and collecting information needed for the analysis. Once this

experience is gathered, failure analysis would be more effective. Also, they pointed that each organization has the responsibility to demonstrate the benefits of using the system to their technicians and motivate them to allocate time to consult the ES when applicable. The stakeholder feedback is reflected in the same levels that the needs and requirements were expressed in order to demonstrate their satisfaction.

On an operational level, an accurate report on the Failure Mechanisms (FM) of the failure helps to take proper remedial actions. In this way, a repetitive appearance of the same FM could be stopped. Furthermore, improving data credibility would lead to more precise maintenance planning. Currently, simple failures are being overlooked. The failed components are replaced by new ones and only if the failure is more frequent, then experts perform an investigation. In the case of complex failure, a more detailed investigation takes place by experts. In both cases, there are high economic and time costs involved. The proposed system can reduce the cost of an investigation by experts and provide solutions in less time.

On an organizational level, structuring failures and symptoms could help create databases with information related to the failure. For example, evidence about date, place, system, component, treatment, technicians, symptoms and causes could be inserted in a database. This could lead to proper documentation of the failure history of the company. Preserving such knowledge in an organization is crucial and has great economic advantages. The stored data would expedite reliability calculations and enable the implementation of predictive maintenance strategies.

Expert opinion was also used during the knowledge elicitation and representation phase. The opinion of the supervisors and scientific literature were employed to validate the completeness of the failure features and failure matrix. The relationship between failure mechanisms and failure features was also reviewed several times to ensure accurate failure mechanism identification.

At last, expert opinion was used as a validation method via a questionnaire handed to one of the stakeholders after using FAME-X on a case study. The results are presented and discussed in the Section 8.4.3.

8.3 SINGLE-CASE MECHANISM EXPERIMENTS

A single-case mechanism experiment in validation research is the stimulation of the model and the explanation of the response in terms of mechanisms internal to the model. In this context, various case studies of mechanical component failures found in the literature and one from the industry were analyzed by FAME-X. The aim is to investigate how accurate already known failure mechanisms can be identified and how the production rules affect this process. The experiments do not show the satisfaction of a specific requirement as accuracy is not a requirement. However, the experiments contribute to the stakeholder wishes which is to now accurately the FM responsible for a failure.

At this point it is important to define accuracy. Based on the input provided, the tool would suggest a list of possible failure mechanisms. The amount of correctly identified FM in this list over the amount of FM actually present in the failure is what defines accuracy here. It is a qualitative measure that assists to validate the performance of the tool. For example, if fatigue

is suggested from the tool after the analysis and fatigue is the only responsible FM for the failure, then the tool has accurately identified the FM. If fatigue and corrosion are suggested than the accuracy is lower.

Sources for the case studies are Ramachandran [44] and Jones [47] who performed a Root Cause Analysis (RCA) and documented the findings in their work. The case studies were selected to be suitable for the validation model. Only mechanical failures of metallic parts were included. The failure information that were used to feed FAME-X were chosen carefully. Only features that can be extracted by visual macroscopic examination were allowed. This ensures that the user during validation had no more information available than during the intended use in a real world analysis.

The failure mechanisms that were tested were chosen randomly. Some of them are Low Cycle Fatigue (LCF), fatigue (general), pitting corrosion and a more complicated case where both adhesive wear and static overload were present. The obtained results are quite promising. In the case of LCF, FAME-X was able to successfully identify the failure mechanism with high accuracy, as it was its only suggestion. Accordingly, in the case of general fatigue, the tool was able to diagnose it during the first level factors stage with high accuracy. Further investigation during the second level factors stage indicated impact fatigue and LCF, which both could be true based on the failure description. Pitting corrosion was among top 3 results during the corresponding case study. After performing minor adjustments in the production rules, the tool could suggest pitting corrosion with the highest confidence. However, the accuracy was lower because more than one failure mechanism was present with lower confidence values. FAME-X performed well in resolving a more complicated case where two FM were present. The first stage results showed wear and static overload as the responsible failure mechanisms. The second level factors stage indicated adhesive wear with the highest confidence followed by abrasive and fretting wear with significantly lower confidence values.

A case study, offered by Nederlandse Spoorwegen (NS), regarding the failure of bearings was also analyzed by FAME-X. The bearings failed by surface fatigue, a common FM for this type of equipment. Macroscopic examination revealed spalling on the outer surface of the inner ring of the bearing. After feeding all the available information to the tool, it suggested accurately that surface fatigue is the responsible FM. This case was analyzed with an earlier version of the tool where the two level factors methodology was unavailable.

8.4 TECHNICAL ACTION RESEARCH (TAR)

Technical Action Research (TAR) suggests the use of a prototype in a real world problem. In single case mechanism experiments, the user of FAME-X is the designer. In TAR, the users are the stakeholders of the project. The difference in this validation method is that the users do not possess the knowledge of the designer on the internal mechanisms of the tool. This makes the results less biased and brings the experiment closer to realistic conditions. This method aims to access the accuracy of the suggestion when the tool is used by non-experts and unfamiliar with the mechanisms of the tool people. It tests mainly the conformity of the tool

with R10 which states that the tool should be comprehensible by non-experts in failure analysis.

Two university colleagues and a company representative became the users of FAME-X in these experiments. The first user has no background in physics of failure and mechanical engineering. The second user has limited background in physics of failure. The last user is an experienced maintenance engineer from NS. The input of the current users can approximate the responses of an unexperienced system operator, an experienced technician and a maintenance engineer, respectively. None of them is expert in failure analysis. The diversity among their backgrounds could provide insight on the usability of the system by different types of potential industrial users. FAME-X is designed for non-experts in physics of failure, however, several discussions have taken place to find the suitable users in terms of background and role within industries.

The experiment started with handing over instructions and a case study to the participants. The case study refers to the failure of a Low Pressure Turbine Rotor (LPTR) blade during a test run [44] by the fatigue mechanism. The specific type of fatigue was not diagnosed for this case study. Time to failure, materials and detailed images from different angles are the information provided for the experiment (more details can be found in Appendix C). The failure mechanism was not revealed to the users until the end of the experiment to ensure that their answers will not be affected. The answers that they provide to the questions of the system are documented in Table 8-1 and are discussed below. In addition, a questionnaire that captures the opinion of the user about the system and its usability was handed after the experiment. The responses are demonstrated in Table 8-2 and they are discussed separately for each experiment and user in the following sections.

8.4.1 Experiment 1

A good first result is that the first user, the least experienced in physics of failure, managed to understand the content of the questions and respond accordingly. His responses are documented in Table 8-1. However, his comprehension regarding the questions does not lead to correct answers for all the questions. For instance, on the question “Describe the medium with which the failed part is in contact with by selecting one or more of the following categories”, his answer was falsely “solid”. The question is accompanied with an explanation text pointing that the contact medium should be selected according to the loads exerted on the failed component. Hence, in this case the correct answer is “Gas” because the air applies the highest load on the blade of the turbine. Moreover, on the question “Characterize the failed component according to its life time to one of the following categories” he selected “Not used as intended by the manufacturer”. In the case study description, it is mentioned that the blade failed within hours of operation meaning that it is new. Also, the answer he provided could not be deducted from the information given in the case study.

According to the answers, it appears that the user could not extract all possible fractographic characteristics from the images of the failed component. The participant answered partially correctly to the corresponding question by selecting “Jagged path cracks”, which is the most

profound answer based on the images. Though, he could not recognize the beach marks that appear in one of the images and are critical for fatigue diagnosis.

The suggestion of FAME-X is that the blade failed by creep. Fatigue was not included in the list of suggestions at all, whereas it should be. That is because the user identified that the blade is subjected to repeated or cyclic load. Hence, the fatigue should be one of the suggestions. This revealed that some of the productions rules regarding fatigue are strict and excluded the mechanism from the suggestion list. After proper correcting actions, fatigue was suggested as a mechanism when the same input was reentered to FAME-X. As it can be seen in Table 8.2, the participant reported that the questions are easy to understand and even easier to answer. However, the latter is not reflected in his answers. Also, the participant believes the tool can assist both operators/technicians and engineers in failure mechanism identification. It can be concluded by this experiment that the questions are understandable even to the most inexperienced user. However, answering the questions is not always straightforward.

8.4.2 Experiment 2

In this experiment, the user of FAME-X has a better physics of failure background but it is still rather limited. In spite of that, he managed to identify correctly fatigue as the FM of the LPTR blade. The tool finally suggested him LCF fatigue with confidence 0.5 as a specific FM. This (quantitative) result cannot be validated, because it is not concluded in the case study by Ramachandran [44] and the required information to reach that conclusion are not available. The achieved confidence value is justified given that some questions were answered incorrectly by the user.

Table 8-1 shows that most of the questions were answered correctly according to the information provided in the case study. A critical false answer was given for the question “Do you observe plastic deformation or elongation on the failed component?”. The user replied “Yes”, while no plastic deformation is observable in the images of the failed blade. Also, the material of the blade is a super alloy which has a brittle behavior, as the user correctly identified. This observation reveals the need to create a new module within FAME-X where the user will be informed in case he or she provides an answer contradicting a previous one. This could be beneficial in two ways. The users could receive educating information that help them develop professionally and the system could receive accurate information leading to accurate suggestions. This idea is also proposed in the final chapter.

The participant in this second experiment also reported that the questions are easy to understand and to answer. According to his opinion, FAME-X could be useful for both operators/technicians and engineers in identifying FM. He is satisfied with the user-friendliness of the tool, while he recommends to improve the sequence of the questions and to make the transition among them smoother. His recommendations were taken into consideration and the sequence of the questions changed as the questions belonging to the same category were grouped together. A smoother transition among the questions requires intermediate text and an additional screen. This option is rejected since it would increase the overall time of analysis.

8.4.3 Experiment 3

In this experiment, the user of FAME-X is a stakeholder from NS. The experienced maintenance engineer used FAME-X to diagnose the FM responsible for the failure of the LPTR blade. The given answers are documented in Table 8-1. The user answered most of the questions correctly and consequently managed to identify that fatigue during the first stage of the analysis. At the second stage, LCF fatigue with confidence value 0.75 was diagnosed. The confidence value is larger than the one in the second experiment due to the larger percentage of correctly identified failure features.

The NS stakeholder appears to be enthusiastic about the design of FAME-X and the benefits that can bring to the failure reporting processes. Her feedback is documented and presented in Table 8.2. The participant found the pictures used as visual aids to be quite nice and helpful. Also, the participant reports that Web access enhances portability and hence it is a big plus for the deployment of the tool within an organization. Furthermore, the tool smoothly diagnoses FM by asking easy to answer questions. This improves significantly the current failure reporting norms where the systems ask the user directly to select the most the FM without any guidance. In the question if she would suggest the tool to her organization, the answer was “maybe”. This is because other NS engineers seemed reluctant to use the “kennisbank” tool which is described in Chapter 2 because they already possessed the knowledge of the tool. However, the scopes and the users of the two tools are quite different. Nevertheless, she concludes that the system can certainly add value to the current failure reporting process and enhance failure analysis by improving the credibility of the current FM registrations. Also, the technicians can gain knowledge from the supporting material of the questions (i.e. photos, explanations).

8.5 CONCLUSIONS

The current chapter is dedicated on validating FAME-X. The validation focuses on the core of the tool which is the accuracy of its suggestion. This was achieved by using the single-case mechanism experiment and TAR methods. The first method was used iteratively during the development of the FAME-X and revealed several flaws on the production rules which then were corrected. It was also used for the validation of the FAME-X prototype together with TAR. The results are quite promising with the tool managing to identify accurately the FM responsible for the failure in most of the experiments.

The participants of the experiments reflected their experience of using FAME-X and their general opinion via questionnaire handed to them after the end of the experiments. FAME-X contains easy to understand and to answer questions according to their opinion. Also, the visual aids and the text explanations promote a user friendly environment. Finally, a NS valuable stakeholder of the project reports that FAME-X can certainly add value to the currently problematic failure reporting procedure.

Table 8-1. Questions asked by FAME-X and responses given by the users during the case study. Note that the sequence of questions is respected only if correct answers are given.

Questions		Correct answers	User 1	User 2	User 3
1	What are the loads that the component was subjected to?	Repeated	Repeated	Repeated	Repeated
2	Is the component broken or severely cracked?	Yes	Yes	Yes	Yes
3	Describe the fracture by selecting one or more of the following fracture characteristics:	Beach marks	Jagged lighting path cracks	Beach marks, shear lips	Beach marks, Ratchet marks
4	Does the load have an impact nature?	No	No	No	No
5	Describe the appearance of the fracture by selecting one or more of the following descriptions:	Bright rock candy texture	Bright rock candy texture	Bright rock candy texture	Woody dull fracture
6	Describe the surface condition of the part by selecting one or more of the following:	Dented	Cracks	Cracks	Dented
7	Describe the medium with which the part is in contact with by selecting one or more of the following categories:	Gas	Solid	Gas	Gas
8	After examining the component for corrosion products (rust), classify the findings in one of the following categories:	No corrosion products	No corrosion products	No corrosion products	No corrosion products available
9	Characterize the failed component according to its life time to one of the following categories	New	Not used as intended	New	New
10	Which of the following internal stress types can you identify on the component during its normal operation?	Tensile, shear	Not known	Not known	Tensile, shear
11	Classify the temperature of the component during its normal operation in one the following categories:	High temperature	High temperature	Not known	High temperature
12	Do you observe plastic deformation or elongation on the failed component?	No	No	Yes	No

13	Classify the fracture of the failed component in one of the following categories:	Brittle	Brittle	Brittle	Ductile
14	Results on generic FM	Fatigue	Creep	Fatigue	Fatigue
15	Classify the material of the component in one of the following categories:	Super alloy	Cast iron	Super alloy	Super alloy
16	Classify the surface quality of the component in one of the following categories:	Low	High	Low	Low
17	Results on specific FM	-	Stress rupture conf. 0.5	LCF conf. 0.5	LCF conf. 0.75

Table 8-2. Questions and responses regarding the experiment conducted with 3 users. The questions 1 to 4 are answered in a linear scale from 1 to 5, with 1 being "Very difficult" and 5 being "Very easy". Question 6 is answered with "Yes/No" and questions 6 and 7 are answered in free text.

	Questions	User 1	User 2	User 3
1	How easy is it to understand the questions asked to the user?	4	4	4
2	How easy is it to answer the questions?	5	4	4
3	According to your opinion, could FAME-X assist operators/ technicians (users with limited knowledge) to identify failure mechanisms?	5	5	5
4	According to your opinion, could FAME-X assist engineers to identify failure mechanisms?	4	5	4
5	Would you recommend the system to your organization? (intended for company stakeholders)	n.a.	n.a.	Maybe
6	What would you improve?			
	User 1	Not answered		
	User 2	Improve sequence of questions and make flow smoother		
	User 3	Treat also electric failures, include pictures related to the application of each stakeholder, engineers need extra motivation in order to use the system.		
7	Other remarks?			
	User 1	Not answered		
	User 2	It is user friendly		
	User 3	Nice and helpful pictures. Web access enhances portability and hence it is a big plus for the deployment of the tool. The tool smoothly diagnoses FM by asking easy to answer questions (current failure reporting systems ask the user directly to select the most the FM), The system can add value to the current failure reporting process and enhance failure analysis by improving the credibility of suggestions on the most probable FM.		

CHAPTER 9

FAME-X PROTOTYPE

9.1 INTRODUCTION

This chapter finalizes the design cycle of FAME-X, as it constitutes together with Chapter 8 the validation phase of FAME-X. Chapter 8 was focused on testing the tool on its core, i.e. the accuracy of its suggestions, and the conformity with requirements from the stakeholders and system levels. Chapter 9 focuses on presenting the layout of the tool and properties such as functionality, tecno-economic realisability and construction. The properties are compared against the requirements, with emphasizing on the system and system element level requirements. Furthermore, this chapter completes the design cycle by investigating the sociotechnical embedding and the impact of the tool.

9.2 LAYOUT

When the user launched FAME-X first encounters the title screen illustrated in Figure 9-1. The logo of the University of Twente, the title of the tool and the developer's name are presented in this first screen. Then, novice users have the option to see an introductory screen explaining the tool's purpose and the process that is going to follow (Figure 9-2). Experienced users have the option to skip this screen by pressing the corresponding button.

Figure 9-1. Title screen as depicted to the user.

Figure 9-2. Optional intro screen.

The main body is composed of the prompt of the question and the available options which are shown in the form of radio buttons, simple buttons or check boxes, depending on the nature of the questions (see details in Section 7.2.5). The explanation part is empty for very simple questions -in terms of terminology- and incorporates text and images explaining the question's content for more complex questions. Figure 9-3 shows the use of text fields with explanations for the terms *static* and *repeated* load for the user.

FAME-X
Service life conditions

What are the loads that the component was subjected to?

☐ Static

☒ Repeated

☐ Not known

If you are unfamiliar with the types of Loads, find out here:

- Static load:
A static load does not change with time. It is always the same. For example, the weight of a beam is a static load.

- Repeated load
A repeated load or a cyclic load repeats itself over time. For example, imagine when you are blowing up a balloon with your mouth. You exhale the whole air you have gathered, and the balloon gets bigger. At some point you have to inhale more air in order to continue. The balloon at that point start growing. When you blow in again, it starts growing once more. The balloon at that time is subjected to a repeated load. Typical industrial components suffering a cyclic load, are bearings, shafts, fans, etc.

Next

Figure 9-3. Question screen where explanation is given by text fields.

When answering the question requires the investigation of visual features, images and text are used to assist the user in the investigation (Figure 9-4).

FAME-X
Post-mortem characteristics

Describe the appearance of the fracture by selecting one or more of the following descriptions:

☐ Dull woody texture

☐ Bright rock candy texture

☐ Flat fracture

☐ Perforated

☐ Caving around fracture

☐ None

If you are not familiar with fractures, find out here:

Dull woody fibrous texture is a characteristic of a ductile fracture. A bright rock candy fracture surface is observed in brittle fractures. Flat surfaces are also a characteristic of brittle fractures, whilst ductile fractures show extensive deformation. Impact fracture cause perforation and caving around fracture.

Dull woody texture

Bright rock candy texture

Perforated surface with caving around fracture

Next

Restart analysis
Back
Exits

Figure 9-4. Question screen using images to explain the terminology.

Questions are asked according to the scheme presented in Chapter 7. The first part of the questions, covering the Failure Mechanism (FM) family identification, ends with a result screen as shown in Figure 9-5. This screen provides the general categories of failure

mechanisms that could have caused the failure. The tool then asks the user to choose either to further continue the analysis for the detailed failure mechanism identification or to restart the analysis. A click on the next button enables this second (detailed) part of the analysis for each suggested failure mechanism category separately.

Figure 9-5. Result screen showing the potential failure mechanism families.

A screen appears to inform the user on the FM family to be analyzed. An example screen for fatigue is shown in Figure 9-6. The actual analysis part then proceeds with question screens as before.

Figure 9-6. Screen indicating which failure mechanism family is going to be identified.

Once it is completed, a results screen appears revealing the exact FM. It contains a list of the possible FM with their confidence values. Only the FM with confidence values greater than zero are included in the list and sorted in descending order of confidence value. Figure 9.7 shows such a results screen for corrosion. After one failure mechanism family has been analyzed, the tool continues with the remaining FM families of the list until they are all covered.

Figure 9-7. Final screen presenting the detailed results for the corrosion failure mechanism family.

9.3 INTEGRATION IN FAILURE INVESTIGATION PROCEDURE

To assess the root cause of a failure, a user typically has to go through a failure investigation procedure to collect the necessary information and deduce from that information the right failure cause. This is a generic procedure which potentially applies to every system. With the introduction of FAME-X, which interacts with the user in order to diagnose the FM responsible for the failure, this process is changed slightly, as part of the reasoning and deduction is taken over by FAME-X.

Systems have a hierarchical structure which can be decomposed in several levels depending on the complexity of the system. At the highest level, there is the system itself. One level lower, there are the subsystems that compose the system. At the lowest level, there are the components.

The failure investigation procedure starts with the inspection of the failed system. The aim is then to locate the subsystem and subsequently the component responsible for the overall failure. After that, the user must macroscopically examine the failed component, either by naked eyes or with the use of a magnifying glass, to identify certain failure features, e.g. cracks, dents, beach marks. At this stage, FAME-X takes over as these failure features are the input to FAME-X. The tool guides the user on what information are important by asking relevant questions. Once the input is provided, the tool makes inferences and provides suggestions on the most probable failure mechanisms in the form of a list. If the user considers the tool's answer sufficient, then the procedure finishes, otherwise the user must repeat the procedure in order collect more information related to the failure. The failure investigation procedure, including the part that is covered by FAME-X, is schematically illustrated in Figure 9-8.

Figure 9-8. Role of FAME-X in the failure investigation procedure.

9.4 FUNCTIONALITY

Functionality is the ability of the system to do the task for which it was intended. The required functions or the qualities of the system are specified in the requirements of the Chapter “Requirement Engineering”. Hence, the conformity of the prototype of FAME-X to the requirements is an indicator for the functionality of the tool. Here, a discussion takes place regarding the fulfillment of the requirements at the different levels, i.e. stakeholder level, system level, system elements level.

On the *stakeholder level*, FAME-X fulfills all mandatory requirements (see Table 5-1, requirements 1 – 10). Within two years an Expert System (ES) has been developed, validated, delivered and accompanied by a report. EXSYS Corvid, the development platform of FAME-X, provides the capability to update the tool and to maintain it as desired by the customer. In its current version the tool operates without any technical problem. The adopted design approach targets non-experts in physics of failure as potential users. Corresponding measures were taken to ensure that the system is comprehensible by its intended users. These are the explanatory images, use of simple language and insertion of explanatory text fields when scientific terminology could not be avoided.

On the *system level*, FAME-X fulfils almost all mandatory and key requirements (see Table 5-1, requirements 11 – 20). The user can interact with the tool via the Graphical User Interface (GUI). Images and text explanations are incorporated to the GUI to ensure comprehensibility by unexperienced personnel. Moreover, as it is described in Chapter 5, all the FM mentioned in Requirement 12 (R12) are treated by FAME-X. The tool is even capable of identifying these mechanisms in greater detail as it treats all the basic FM of mechanical components made from metal. FM diagnosis is accompanied by a confidence value to demonstrate the validity of the suggestion with respect to the input provided by the user. If all confidence values are zero, the tool will not be able to suggest any FM, as apparently no support or prove for any specific FM has been found or reported. In this case, the user is notified that the tool is unable to provide him a suggestion and he should reconsider his input. Furthermore, by the end of the project FAME-X was not available to mobile devices due to technical issues. Web access can be achieved by minor adjustments related to the GUI. Hence, R11 is partially satisfied. Also, it can be operated as a standalone application in case accessibility via the Web is not desired or available. The other mandatory requirement that is partially fulfilled is R15, i.e. that

tool should be able to demonstrate its decision making path. EXSYS Corvid does offer the capability to incorporate a tracing module that keeps tracks of all production rules used to reach a certain decision, but this module has not been yet activated on FAME-X. It is therefore not yet possible to count the number of questions required, and thus R15 cannot yet be validated. Finally, R20 is fulfilled since EXSYS Corvid ensures that its products are accessible by multiple users.

On the *system elements level* (see Table 5-1, requirements 20 – 27), most of the requirements are satisfied. The tool has no limitation on storage capacity since it connects with servers and databases. FAME-X is not programmed to communicate with a database because it not necessary. Furthermore, the EXSYS Corvid platform is only accessible and editable by the developer. The users of FAME-X can only perform the analysis but not access EXSYS Corvid. This automatically fulfills R23 and R24 that call for integrity and consistency of the knowledge base when accessed by concurrent users. R26 and R27 which control the layout of the questions are also fulfilled as shown in Section 7.2.5 which describes the design of the questions.

The acceptance of the tool by the stakeholders is also reflected by a questionnaire, which captured the opinion of the stakeholders (see Appendix C). Stakeholders from the University of Twente reported that they were able to understand and answer the questions easily. One of them commented that the GUI feels user-friendly. The company stakeholder reported that the tool feels nice and easy to use and that it could definitely add value in failure reporting procedure. The latter opinion contributes significantly to the higher level validation of FAME-X. Company stakeholders are of high importance as they could be potential customers and final users of FAME-X.

9.5 TECHNO-ECONOMIC FEASIBILITY

As discussed earlier in Chapter 4, the design cycle stops before the implementation of the artifact in the real world. Scaling up the design, designing for mass production, embedding the design in the real world and evaluating its performance is some of the functions of the engineering cycle. Here, a short discussion takes place regarding the technical and financial feasibility of implementing FAME-X on the real world. Questions like “what does it need to implement FAME-X to the industry?” and “is it worth it to implement FAME-X to the industry” are answered here.

Developing FAME-X on an expert system shell like EXSYS Corvid disentangles industrial deployment mechanisms. Customers require only a Web link to access and use the tool on any device. EXSYS Corvid offers fast Web-enablement through Java delivery. A server provides the required files for the system to run on the client machine. The standalone version requires the installation of the files on the client machine. The disadvantage of this latter approach is that for each standalone application a license is needed which increases the overall costs drastically.

FAME-X can bring significant benefits to an organization and can decrease maintenance operational costs. From a financial point of view, FAME-X could be positive for an organization. The development platform EXSYS Corvid is the only significant cost. However, it can be used for the development of numerous Web-based applications. This would divide the costs over different projects. Besides ES shells, Section 3.3.5 suggests other (lower cost)

options to develop a failure mechanism identification tool. The failure analysis methodology presented in this thesis can be followed by the stakeholders to create similar applications. Knowledge on the exact mechanisms that lead components to failure assist in adopting the appropriate countermeasures. Ineffective maintenance actions are rather unprofitable for companies. Furthermore, replacing experts with the tool in simple failure cases could have immediate financial advantages. Experts are quite expensive and hence they should be hired only in complex cases where FAME-X cannot provide solutions or the root cause is required to be found.

The generic approach adopted for the tool makes it applicable to several types of industries and failures. As failure mechanisms are fundamental processes acting on a material level, FAME-X's applicability is independent from types of industry.

FAME-X is a complete and functional ES. Cosmetic type changes could be though required for the customers. Each company desires a specific layout for the tool. Colors, images, fonts and text can be changed according to the desire of the costumer. Moreover, a potential need to connect the tool with existing databases, can be fulfilled in consultation with the developer. In this case, minor changes in the architecture of the system have to be made on the EXSYS Corvid platform.

9.6 SOCIO-TECHNICAL MAPPING AND IMPACT

Socio-political processes surround and penetrate design processes within organizations. In order to avoid potential conflicts, a protected space must be established and maintained for the design. Embedding the design in the wider societal context must be also controlled by taking proactive measures and collaboration with stakeholders. The elements and stakeholders that are a challenge for FAME-X to be societally embedded are presented in Figure 9-9 and are discussed below.

Portable devices

A prerequisite for the realization of the proposed decision support system is the technological feasibility. Before the implementation of portable devices on the everyday maintenance duties, a system like the proposed system would be very indifferent for industries. Consultancy by an expert in root cause analysis was the norm. However, the high costs of experts prohibit their frequent use even in large organizations. Technological advancements which enhanced the communications in every context generated new wishes and opportunities. Now, portable devices can bring "virtual consultants", like FAME-X, on site at much lower costs, which would largely extend the applicability of root cause analyses.

Figure 9-9. Socio-technical mapping of the ES

Compatibility and connectability

Certain stakeholders wished the communication of FAME-X with the databases and maintenance management systems. As explained previously, this option could be realized but is currently unavailable for the tool. In case of a future industrial implementation, a collaboration must be established with the IT department of the customer or with other companies, which produce the systems that the customer is using, in order to connect the systems and resolve any potential compatibility issues.

AI algorithms and internet accessibility

Another technological advancement that makes the development of FAME-X possible is Artificial Intelligence (AI). The ES is based on rule-based reasoning, a concept generated in the field of machine learning, that it is used to capture the problem solving methodology. In addition, internet wide accessibility promotes the creation of systems that assist in every day professional duties such as maintenance operations. FAME-X can be delivered to multiple users via the Web with high speeds.

Niches in the maintenance field

Throughout the years, the importance of the maintenance function has grown. Optimization of maintenance plans yields significant benefits for industries. During the previous decades, maintenance was considered to be a necessary 'evil' from the majority of companies. A procedure that must be followed in order to avoid unexpected failures. A conservative practice that evidently has high cost. However, this old-fashioned mentality has gone through big changes in the last years, especially in large organizations. Industrial maintenance has shifted from conventional methods, like run-to-failure maintenance or preventive

maintenance to condition based maintenance and predictive maintenance. For the practice of the last two, it is mandatory to better understand the condition of the asset. Hence, many projects are funded to research new ways for condition monitoring and failure diagnosis. FAME-X is a product of such niches.

End-user challenges

Discussions with stakeholders revealed that even if their organization deploys FAME-X, the biggest challenge is to persuade the maintainers or technicians to use it. The main responsibility of the technicians/ maintainers is to keep the production “up and running”. Reporting failures is a secondary task. In addition, FAME-X contains scientific terminology which can be a hurdle for its successful implementation. However, the validation tests reveal that the content is rather comprehensible by non-experts. Still, it remains a challenge for the companies to find the suitable personnel within their organization to use FAME-X.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 INTRODUCTION

This final chapter draws the conclusions of the design procedure of this thesis. Firstly, in Section 10.1.2 it summarizes the most important conclusions and answers to the knowledge questions of the thesis. Finally, in Section 10.1.3 it identifies several directions of further research.

10.2 CONCLUSIONS

The aim of this work was to solve the design problem and answer knowledge questions. The design problem was the development of a decision support tool for failure mechanism identification. The knowledge questions were:

- (i) *which information regarding a failure is needed to decide upon proper remedial action?*
- (ii) *how to perform a macroscopic failure analysis of mechanical components?.*

The conclusions drawn after completing the design process provided below. Regarding the design problem, the conclusions are introduced on the same levels as the requirements are defined. At the systems level, the following are concluded:

- A failure mechanism identification Expert System (ES) prototype entitled FAME-X has been developed, tested and validated. The design cycle is described in detail in this thesis.
- FAME-X provides decision support to non-experts in physics of failure (e.g. system operators, technicians, maintainers). Interviewed stakeholders confirm that the tool can be useful for non-experts. The graphical user interface is reported to be user-friendly.
- FAME-X's accessibility via the Web has not been yet realized due to technical issues. In principal, the tool can be uploaded on the Web but the GUI lacks the desired appearance.
- FAME-X follows a generic failure mechanism (FM) identification procedure applicable to metallic components. An extensive list containing all common mechanical and chemical FM is included in the knowledge base of the tool. The diagnosis relies upon the investigation and reporting of several well defined features related to the component's service life, materials, time to service of the component and post-mortem characteristics.
- Suggestion of the dominant failure mechanism is accompanied by a confidence value that reveals the degree of validity of the suggestion. This value is based on the failure analysis knowledge incorporated into the system and the evidence provided by the

user. The user can judge whether or not to trust the suggestion based on the confidence value.

At the stakeholder level, the conclusions are the following:

- FAME-X could assist operators to fulfill successfully their failure reporting duties as some stakeholders report.
- FAME-X could potentially educate operators in the physics of failure. The explanations provided during the analysis and the rules incorporated into the tool can be used as educating material. In this way, the personnel can develop awareness on the failures of the equipment and their causes.
- FAME-X provides a uniform vocabulary. This helps in organizing and structuring reports and avoiding miscommunications.
- FAME-X provides knowledge-based suggestions by limiting the experience factor of the user during failure registration. Both novice and experienced operators could benefit from the tool on conducting failure diagnosis. Of course, a more experienced operator can identify faster and more accurately the failure features than a novice one.
- The simple and user-friendly GUI can motivate the user in engaging in failure analysis.
- FAME-X's way of selecting and registering failure features eliminates the current free text fields in a typical CMMS that create vagueness, confusions and misinterpretations.

At the company level, the conclusions are the following:

- FAME-X could substitute the expensive expert failure analyst on less complex cases.
- FAME-X could assist in a reduction of costs because proper remedial actions can be taken. Proper diagnosis of FM assist maintenance planners to decide upon proper remedial action. Consequently, tailored and focused maintenance practices lead also to cost reduction.
- Documenting FM on databases based on FAME-X's suggestions could contribute to make a failure archive where different kind of information (e.g. output of FMECA) can be connected to FM. This enhances the view of the decision makers and also securely stores and preserves failure related knowledge within a company.

Regarding the knowledge questions, the detailed answer are:

- *Which information regarding a failure is needed to decide upon proper remedial action?*

In Chapter 6, it has been concluded that this is given by the failure identity. The two elements of the failure identity are: the failure mechanism and the root cause. Failure mechanisms describe "how" a failure occurred and root causes provide insight in "why".

- *How to perform a macroscopic failure analysis of mechanical components?*

Macroscopic failure analysis is part of a larger more detailed analysis, the Root Cause Analysis. RCA steps have been presented in Chapter 6. From the general RCA procedure, it is distilled that the analysts should focus on the collection of failure

features. The features are classified in four broad categories: service life conditions, materials, time to service and post mortem characteristics. The collection and study of the features according to the physics of failure can lead to the determination of the failure mechanism responsible for the failure.

10.3 RECOMMENDATIONS

While this thesis describes the design of an expert system for failure mechanism identification, it also poses some new design directions on how to proceed further. These directions will be discussed below.

- FAME-X treats only one of the elements of the failure identity which is the failure mechanisms. Deciding upon proper remedial actions also requires root cause diagnosis. Hence, a next step for FAME-X would be the extension of its methodology to root cause analysis.
- Currently, the user relies on the confidence value of the suggestion to make a decision. However, introduction of probabilities can lead to more solid suggestions on the most probable failure mechanism.
- It is common, especially for complex failures, that more than one FM is present. Sometimes a failure starts with one mechanism and finishes with another. In RCA a distinction between primary and secondary FM takes place. However, FAME-X does not take that distinction into account at the moment. It can only suggest that more than one FM possibly are responsible for the corresponding feature that have been identified. An improvement for the tool would be to add the ability to distinguish between primary and secondary failure mechanisms. This would require additional fractographic and fabrication information of the failed component.
- In terms of materials, FAME-X treats only metallic components. A potential extension of the system could be to include other materials like ceramics, polymers and composites. The study of these materials and how the various FM are related to them could extend the FM matrix and consequently the capabilities of the tool.
- FAME-X investigates only mechanical components which face mechanical and chemical FM. An extension towards electronic components and their FM is an interesting future improvement for the stakeholders.
- Accordingly, the introduction of new failure features could lead to a more accurate diagnosis. Evidence from laboratory investigation and Non Destructive Testing (NDT) could be integrated with the ones from macroscopic inspection to support the diagnostic process.
- In Chapter 2, it was observed that the user of the second experiment answered contradictively in two questions. A recommendation would be to introduce a new module with rules that can handle conflicting input.
- The current level of graphics of FAME-X is sufficient for demonstration purposes. However, significant improvements can be made on the layout of the tool. This can be

accomplished by writing custom HTML and Java code, and integration with adobe flash. The EXSYS Corvid platform makes these options available.

- A necessary future action is the further validation of the tool. Industrial implementation and experiments with the intended users (i.e. technicians, operators, and maintainers) can give insight on the usability of the tool. In this way, the amount of contribution on the main stakeholder goal, which is the decision support of the non-experts, can be determined.

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APPENDIX A

QUESTIONNAIRE FOR STAKEHOLDER NEEDS IDENTIFICATION

This questionnaire was given to stakeholders during the identification of their needs phase. The questions are the following:

Industry

1. What types of machines do you have? Which are the most critical machines/ components?
2. What are the most common failure mechanisms you face?
3. An expert system of your interest should focus on the most dominant failure mechanisms or have a generic approach?

Technology

4. Is there a system that you register the occurring failures?
5. Are there any available data regarding failures, condition monitoring or inspections? If yes, how big is this database and what is the data format?
6. Do the operators / technicians/ maintainers use portable devices on their duties?

Procedures

7. What is the procedure following after a failure? Who is responsible to investigate?
What is his educational background?
8. How the failure mechanism is currently identified?
9. What happens in case of a complicated failure mechanism?
10. Which information would be useful for the maintenance management department for analysis purposes?

11. If the failure mechanism cannot be found without a more advanced analysis, what other information would be useful to be stored for later usage (e.g. weather conditions, location, severity)?
12. What is the weak part in the current failure analysis procedure? What would you like to be improved?

APPENDIX B

This appendix presents the failure matrix in full scale which was introduced in Section 6.3. The matrix captures the relationship among failure features and Failure Mechanisms (FM) which is denoted by the notation system of Table B-1. The failure matrix is presented in Table B-2.

Table B-0-1: Scalar notation system denoting the relationship between FM and failure attributes.

Notation	Explanation
	Necessary characteristic for the specific failure mechanism of the corrosion family.
	Necessary characteristic for the specific failure mechanism of the fatigue family.
3X	Necessary presence of the feature for the whole family of failure mechanism.
XX	Presence of this symbol strongly suggests the failure mechanism.
X	Presence of this symbol suggests the failure mechanism.
I	Presence of this symbol means the feature does not contribute to the failure mechanism.
O	Presence of this symbol eliminates the failure mechanism.

Table B-2. Failure mechanism matrix.

Primary Identifier	Grouping	Sub mechanisms	Service life conditions			
			Loads			Stress Type
			Static	Cyclic	Impact	Tension
Buckling		Buckling	3X	I	X	O
Corrosion (Material deterioration due to chemical or electrochemical interaction with environment)	Can be identified with visual inspection	Biological corrosion	I	I	I	I
		Crevice corrosion	I	I	I	I
		Unifrom corrosion/ Uniform attack	I	I	I	I
		Galvanic corrosion	I	I	I	I
		Pitting corrosion	I	I	I	I
	Require supplementary means	Intergranular corrosion	I	I	I	I
		Selective leaching	I	I	I	I
		Erosion corrosion	I	I	I	I
		Cavitation corrosion	I	I	I	XX
		Fretting corrosion	3X	I	I	I
	Stress corrosion cracking	Corrosion fatigue	O	3X	I	XX
		Hydrogen damage	I	I	I	X
		Stress corrosion	3X.	I	I	3X
Creep (Plastic deformation)		Creep	3X	I	I	3X
		Stress rupture	3X	I	I	3X
Yielding		Yielding	3X	I	I	3X
Fatigue (Fluctuating loads or deformation)		High cycle fatigue	O	3X	I	XX
		Impact fatigue	O	3X	3X.	XX
		Low cycle fatigue	O	3X	I	XX
		Fretting fatigue	O	3X	I	I
Impact (Impact load of large magnitude)		Impact deformation	O	O	3X	I
		Impact fracture	O	O	3X	I
Static overload		Brittle rupture	3X	O	O	XX
		Ductile rupture	3X	O	O	X
Wear (Undesired change in dimension)	Abrasive wear	Abrasive wear	XX	XX	XX	I
	Non abrasive wear	Erosion wear	I	I	I	XX
		Adhesive wear	3X	I	I	I
		Corrosive wear	I	I	I	X
		Surface fatigue wear	O	3X	I	I
		Fretting wear	3X.	O	O	I

Sub mechanisms	Service life conditions									
	Stress Type		Environmental conditions			Large slender-ness ratio	Geometry prone to stress concentra-tion	Contiguity		
			Operating Temperature					Presence of O2, SO2,CO2	Gaseous	
	Comp ressi on	She ar	Low	Room Temp	High				Stag-nant	Regular flow
Buckling	3X	I	I	I	X				3X	I
Biological cor.	I	I	I	I	X	I	I	3X	I	I
Crevise cor.	I	I	I	I	X	I	I	3X	I	O
Unifrom cor.	I	I	I	I	X	I	I	3X	XX	X
Galvanic cor.	I	I	I	I	X	I	I	3X	I	I
Pitting cor.	I	I	I	I	X	I	X	3X	XX	O
Intrgrnlr. Cor.	I	I	I	I	X	I	I	3X	I	I
Select. Leach.	I	I	I	I	X	I	I	3X	I	I
Erosion cor.	I	I	I	I	X	I	I	3X	O	O
Cavitation cor.	I	I	I	I	X	I	I	3X	I	I
Fretting cor.	XX	I	I	I	X	I	I	X	I	I
Fatigue cor.	X	X	I	I	X	I	X	3X	I	I
H damage	X	I	I	I	X	I	I	X	I	I
Stress cor.	I	X	I	I	X	I	XX	3X	I	I
Creep	XX	XX	O	O	3X	I	I	I	I	I
Stress rupture	XX	XX	O	O	3X	I	I	I	I	I
Yielding	I	I	I	X	XX	I	I	I	I	I
HCF	I	X	I	I	X	I	X	I	I	I
Impact fatigue	I	X	I	I	X	I	X	O	I	I
LCF	I	X	I	I	X	I	X	I	I	I
Fretting ftg.	I	X	I	I	X	I	X	O	I	I
Impact deform	XX	I	I	I	XX	I	X	I	I	I
Impact fractur.	XX	I	I	I	XX	I	X	I	I	I
Brittle rupture	XX	X	XX	I	O	I	XX	I	I	I
Ductile ruptur.	X	XX	O	I	XX	I	I	I	I	I
Abrasive wear	XX	I	I	I	X	I	I	I	I	I
Erosion wear	I	I	I	I	X	I	I	I	I	I
Adhesive wear	XX	X	I	I	XX	I	I	I	I	I
Cor/sive wear	X	I	I	I	X	I	I	3X	I	I
Surf ftg wear	XX	X	I	X	XX	I	X	I	I	I
Fretting wear	X	I	I	I	X	I	I	I	I	I

Sub mechanisms	Service life conditions							
	Contiguity							
	Gaseous	Bio-products		Water				
				Movement				Composition
				Stagnant		Laminar flow	Turbulent flow	Pure
	High speed turbulent flow	Fungus/mold	Soil, mud	Crevices	Flat surface			
Buckling	I	I	I	I	I	I	I	I
Biological cor.	I	3X.	3X.	I	XX	I	O	O
Crevice cor.	O	I	3X	3X	O	XX	O	O
Unifrom cor.	X	I	I	I	XX	X	X	O
Galvanic cor.	I	I	I	I	X	X	X	O
Pitting cor.	O	I	I	X	XX	O	O	O
Intrgrnlr. Cor.	I	I	I	I	X	X	X	O
Select. Leach.	I	I	I	I	X	X	X	O
Erosion cor.	3X	I	I	X	O	O	3X	O
Cavitation cor.	I	I	I	X	O	O	3X	O
Fretting cor.	I	I	I	X	X	X	I	I
Fatigue cor.	I	I	I	I	X	X	I	O
H damage	I	I	I	I	X	I	I	O
Stress cor.	I	I	I	I	X	X	X	O
Creep	I	I	I	I	I	I	I	I
Stress rupture	I	I	I	I	I	I	I	I
Yielding	I	I	I	I	I	I	I	I
HCF	I	I	I	I	I	I	I	I
Impact fatigue	I	O	O	O	O	O	O	O
LCF	I	I	I	I	I	I	I	I
Fretting ftg.	I	O	O	O	O	O	O	O
Impact deform	I	I	I	I	I	I	I	I
Impact fractur.	I	I	I	I	I	I	I	I
Brittle rupture	I	I	I	I	I	I	I	I
Ductile ruptur.	I	I	I	I	I	I	I	I
Abrasive wear	I	I	I	I	I	I	I	I
Erosion wear	I	I	XX	O	O	I	3X	X
Adhesive wear	I	I	I	I	I	I	I	I
Cor/sive wear	I	3X	3X	3X	3X	3X	3X	3X
Surf ftg wear	I	I	I	I	I	I	I	I
Fretting wear	I	I	I	I	I	I	I	I

Sub mechanisms	Service life conditions									
	Contiguity									
	Water			Relative movement			Material properties of the other component		Lubrication	
	Composition									
	Sea water	Contaminated	Inclusions	Static	Moving	Vibrating	Foreign Object is Harder	Potential difference	Poor	Good
Buckling	I	I	I	I	I	I	I	I	I	I
Biological cor.	3X	XX	I	I	I	I	I	I	I	I
Crevice cor.	3X	I	XX	X	O	I	I	I	I	I
Unifrom cor.	3X	I	I	I	I	I	I	I	I	I
Galvanic cor.	3X	I	I	3x	I	I	I	3X.	I	I
Pitting cor.	3X	I	I	I	I	I	I	I	I	I
Intrgrnlr. Cor.	3X	I	I	I	I	I	I	I	I	I
Select. Leach.	3X	I	I	I	I	I	I	I	I	I
Erosion cor.	3X	I	3X	I	I	I	I	I	I	I
Cavitation cor.	3X	I	I	I	I	I	I	I	I	I
Fretting cor.	X	I	X	O	O	3X	O	I	3X	O
Fatigue cor.	3X	I	I	I	I	I	I	I	I	I
H damage	X	I	I	I	I	I	I	I	I	I
Stress cor.	3X	I	I	I	I	I	I	I	I	I
Creep	I	I	I	I	I	I	I	I	I	I
Stress rupture	I	I	I	I	I	I	I	I	I	I
Yielding	I	I	I	I	I	I	I	I	I	I
HCF	I	I	I	I	I	I	I	I	I	I
Impact fatigue	O	O	O	XX	I	I	I	I	I	I
LCF	I	I	I	I	I	I	I	I	I	I
Fretting ftg.	O	O	O	O	I	3X	O	I	X	O
Impact deform	I	I	I	I	I	I	I	I	I	I
Impact fractur.	I	I	I	I	I	I	I	I	I	I
Brittle rupture	I	I	I	I	I	I	I	I	I	I
Ductile ruptur.	I	I	I	I	I	I	I	I	I	I
Abrasive wear	I	I	I	O	3X	O	XX	I	XX	O
Erosion wear	X	X	3X.	I	I	I	I	I	I	I
Adhesive wear	I	I	I	O	3X	O	I	I	XX	O
Cor/sive wear	3X	3X	3X	X	XX	I	X	XX	XX	I
Surf ftg wear	I	I	I	O	XX	X	XX	I	XX	I
Fretting wear	I	I	I	O	I	3X	O	I	X	O

Sub mechanisms	Service life conditions			Materials					
	Contiguity	Surface quality		Type					
	Third particles presence								
		Low	High	Steels	Tool steels	Cast Iron	Stainless steel	Super alloys	Aluminium alloys
Buckling	I	I	I	X	I	X	X	I	X
Biological cor.	I	I	I	X	X	X	O	X	O
Crevice cor.	I	I	I	XX	XX	XX	X	X	X
Unifrom cor.	I	I	I	XX	XX	XX	O	I	O
Galvanic cor.	I	I	I	XX	XX	XX	I	I	I
Pitting cor.	I	XX	I	XX	XX	XX	I	I	I
Intrgrnlr. Cor.	I	I	I	XX	X	XX	I	I	I
Select. Leach.	I	I	I	X	I	X	I	I	I
Erosion cor.	I	X	I	XX	I	XX	I	I	I
Cavitation cor.	I	X	I	XX	I	XX	I	I	I
Fretting cor.	I	XX	I	X	I	X	O	I	O
Fatigue cor.	I	I	I	XX	X	XX	I	I	I
H damage	I	I	I	XX	X	XX	X	X	X
Stress cor.	I	XX	I	XX	X	XX	X	X	X
Creep	I	I	I	XX	X	I	I	I	I
Stress rupture	I	I	I	XX	I	I	X	I	I
Yielding	I	I	I	XX	I	I	XX	I	X
HCF	I	3X	I	XX	I	I	X	I	X
Impact fatigue	I	3X	I	XX	I	I	XX	I	XX
LCF	I	3X	I	XX	I	I	XX	I	XX
Fretting ftg.	I	3X	I	XX	I	I	X	I	X
Impact deform	I	I	I	XX	I	I	XX	I	XX
Impact fractur.	I	I	I	XX	I	I	XX	I	XX
Brittle rupture	I	I	I	I	X	X	I	X	I
Ductile ruptur.	I	I	I	X	I	I	X	I	X
Abrasive wear	3X	XX	O	XX	I	I	XX	I	I
Erosion wear	I	I	I	XX	I	I	XX	I	X
Adhesive wear	O	3X	O	XX	I	I	XX	I	X
Cor/sive wear		I	I	XX	XX	XX	I	I	I
Surf ftg wear	X	XX	I	XX	X	X	XX	I	X
Fretting wear	O	X	I	XX		I	XX	I	X

Sub mechanisms	Materials		Postmortem characteristics					
	Behavior		Fracture					
			Fracture characteristics/crack feature					Fracture appearance
			Ratchet marks	Beach marks	Chevron "V" marks	Thick/Shear lips 45 degrees	Jagged lighting path cracks	Woody texture
Buckling	I	I	I	I	I	I	I	I
Biological cor.	X	X	I	I	I	I	I	I
Crevice cor.	X	X	I	I	I	I	I	I
Unifrom cor.	X	X	I	I	I	I	I	I
Galvanic cor.	X	X	I	I	I	I	I	I
Pitting cor.	X	X	I	I	I	I	I	I
Intrgrnlr. Cor.	X	X	I	I	I	I	I	I
Select. Leach.	X	X	I	I	I	I	I	I
Erosion cor.	X	X	I	I	I	I	I	I
Cavitation cor.	X	X	I	I	I	I	I	I
Fretting cor.	X	X	I	I	I	I	I	I
Fatigue cor.	X	X	X	3X	X	I	I	X
H damage	X	X	I	I	I	I	I	I
Stress cor.	X	X	I	I	I	I	3X	X
Creep	I	X	I	I	I	3X	I	X
Stress rupture	I	X	I	I	I	3X	I	X
Yielding	O	3X	I	I	I	I	I	I
HCF	X	X	3X	3X	XX	O	I	O
Impact fatigue	X	X	3X	3X	I	I	I	I
LCF	X	X	3X	3X	I	XX	I	XX
Fretting ftg.	I	I	3X	I	I	I	I	I
Impact deform	I	XX	I	I	I	I	I	I
Impact fractur.	XX	I	I	I	I	O	I	O
Brittle rupture	XX	O	I	I	3X	O	I	O
Ductile ruptur.	O	XX	I	I	O	3X	I	3X
Abrasive wear	O	XX	I	I	O	I	I	I
Erosion wear	I	X	I	I	O	I	I	I
Adhesive wear	X	XX	I	I	O	I	I	I
Cor/sive wear	I	I	I	I	O	I	I	I
Surf ftg wear	X	XX	I	I	O	I	I	I
Fretting wear	I	I	I	I	O	I	I	I

Sub mechanisms	Postmortem characteristics							
	Fracture			No Fracture				
	Fracture appearance							
	Rocky candy texture	Caving around fracture	Perforated	Blistering	Grooves , gullies, holes	Pitting /spalling/gouging	Cracks	Discoloration
Buckling	I	I	I	I	I	I	I	I
Biological cor.	I	I	I	I	I	X	I	3X
Crevice cor.	I	I	I	3X	I	I	I	3X
Unifrom cor.	I	I	I	I	I	I	I	3X
Galvanic cor.	I	I	I	I	I	X	I	3X
Pitting cor.	I	I	I	I	I	3X.	I	3X
Intrgrnlr. Cor.	I	I	I	I	I	X	I	3X
Select. Leach.	I	I	I	I	I	X	I	3X
Erosion cor.	I	I	I	I	3X	X	I	3X
Cavitation cor.	I	I	I	I	3X	X	I	3X
Fretting cor.	I	I	I	I	XX	X	I	3X
Fatigue cor.	X	I	I	I	I	X	I	3X
H damage	I	I	I	3X	I	X	I	3X
Stress cor.	X	I	I	I	I	I	3X	3X
Creep	I	I	I	I	I	I	I	I
Stress rupture	I	I	I	I	I	I	I	I
Yielding	I	I	I	I	I	I	I	I
HCF	XX	I	I	I	I	I	I	I
Impact fatigue	I	3X	3X	I	I	I	I	I
LCF	O	I	I	I	I	I	I	I
Fretting ftg.	I	I	I	I	3X	3X	I	XX
Impact deform	I	O	O	I	I	I	I	I
Impact fractur.	XX	3X	3X	I	I	I	I	I
Brittle rupture	3X	I	I	I	I	I	I	I
Ductile ruptur.	O	I	I	I	I	I	I	I
Abrasive wear	I	I	I	I	3X.	3X	I	I
Erosion wear	I	I	I	I	XX	3X.	I	I
Adhesive wear	I	I	I	I	3X.	3X	I	XX
Cor/sive wear	I	I	I	I	I	3X.	I	X
Surf ftg wear	I	I	I	I	I	I	3X	I
Fretting wear	I	I	I	I	3X.	3X	I	XX

Sub mechanisms	Postmortem characteristics					Age			Max Confidence
	No Fracture	General				Time in service			
		Plastc deformation/necking	Rust/corrosion products		Broken or cracked				
			Dented	Extended		Localised	New	Medium	
Buckling	I	XX	I	I	XX	I	I	I	70
Biological cor.	I	I	X	XX	I	O	X	X	200
Crevice cor.	I	I	O	3X	X	O	X	X	320
Unifrom cor.	I	I	3X	O	I	O	X	X	110
Galvanic cor.	I	I	O	XX.	I	O	X	X	100
Pitting cor.	I	I	O	3X	I	O	X	X	160
Intrgrnlr. Cor.	I	I	O	XX.	I	O	X	X	-
Select. Leach.	I	I	O	XX.	I	O	X	X	-
Erosion cor.	I	I	O	XX.	X	O	X	X	270
Cavitation cor.	I	I	O	XX.	X	O	X	X	140-160
Fretting cor.	I	I	O	3X	X	O	X	X	310
Fatigue cor.	I	I	O	X.	XX	O	X	X	150
H damage	I	I	O	X.	X	O	X	X	-
Stress cor.	I	I	O	X.	X	I	I	I	290
Creep	I	XX	I	I	X	O	I	XX	50
Stress rupture	I	O	I	I	XX	O	XX	XX	40
Yielding	I	3X	I	I	O	X	X	XX	0
HCF	I	I	I	I	3X	O	X	3X	190
Impact fatigue	3X	I	I	I	3X	I	X	X	290
LCF	I	X	I	I	3X	3X	X	O	160
Fretting ftg.	I	I	I	XX	X	O	X	XX	170
Impact deform	3X	XX	I	I	I	I	I	I	60
Impact fractur.	O	O	I	I	XX	I	I	I	160
Brittle rupture	I	O	I	I	3X	I	I	I	170
Ductile ruptur.	I	XX	I	I	3X	I	I	X	170
Abrasive wear	I	X	I	I	O	O	X	3X	320
Erosion wear	I	X	I	I	O	I	X	3X	240
Adhesive wear	I	X	I	I	O	O	X	3X	240
Cor/sive wear	I	I	I	XX	O	O	X	3X	310
Surf ftg wear	I	X	I	I	O	O	X	3X	240
Fretting wear	I	X	I	3X.	X	O	X	3X	310

APPENDIX C

CASE STUDY OF THE FAILURE OF A LOW PRESSURE TURBINE BLADE

Description

A Low Pressure Turbine Rotor (LPTR) blade failed during a test run causing damage to all blades [44]. The LPTR failed within hours of a test causing extensive damage to the engine. Figure 1 reveals that one of the LTRP blades had fractured near the blade root. The LPTR blade was made by directionally solidified cast nickel-base superalloys with platinum aluminide surface coating. Macroscopic fractographic characteristics can be extracted by observing Figures 2-4.

Figure 1. The fractured turbine blade.

Figure 2. Cross section of the blade showing the fracture.

Figure 3. Magnified picture of fracture surface.

Figure 4. Magnified picture of fracture surface.

Instructions

Once you read the description of the case study you are called to identify the failure mechanism that contributed to the failure of the low pressure rotor turbine blade. To reach the desired conclusion, the information given in the text and in the images have to be combined with information coming from imagining the blade during normal operation. For example, a rotating blade is always subjected to cyclic loads; this information is not given explicitly in the description but it can be deduced by imaging the blade under normal operation.

Failure mechanism

The LTRP blade failed due to fatigue.

Questionnaire

The questionnaire presented in Table C.1 captures the experience of the users during the experiments with the FAME-X prototype.

Table C-1. Questions and responses regarding the experiment conducted with 3 users. The questions 1 to 4 are answered in a linear scale from 1 to 5, with 1 being "Very difficult" and 5 being "Very easy". Question 6 is answered with "Yes/No" and questions 6 and 7 are answered in free text.

	Questions	User 1	User 2	User 3
1	How easy is it to understand the questions asked to the user?	4	4	4
2	How easy is it to answer the questions?	5	4	4
3	According to your opinion, could FAME-X assist operators/ technicians (users with limited knowledge) to identify failure mechanisms?	5	5	5
4	According to your opinion, could FAME-X assist engineers to identify failure mechanisms?	4	5	4
5	Would you recommend the system to your organization? (intended for company stakeholders)	n.a.	n.a.	Maybe
6	What would you improve?			
	User 1	Not answered		
	User 2	Improve sequence of questions and make flow smoother		
	User 3	Treat also electric failures, include pictures related to the application of each stakeholder, engineers need extra motivation in order to use the system.		
7	Other remarks?			
	User 1	Not answered		
	User 2	It is user friendly		
	User 3	Nice and helpful pictures. Web access enhances portability and hence it is a big plus for the deployment of the tool. The tool smoothly diagnoses FM by asking easy to answer questions (current failure reporting systems ask the user directly to select the most the FM), The system can add value to the current failure reporting process and enhance failure analysis by improving the credibility of suggestions on the most probable FM.		

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