Asset information for FMEA-based maintenance

Jan Braaksma

Published by: University of Groningen
Groningen
The Netherlands

Printed by: Ipskamp Drukkers B.V.

ISBN: 978-90-367-5806-2 (book)
978-90-367-5807-9 (e-book)

RIJKSUNIVERSITEIT GRONINGEN

Asset information for FMEA-based maintenance

Proefschrift

ter verkrijging van het doctoraat in de
Economie en Bedrijfskunde
aan de Rijksuniversiteit Groningen
op gezag van de
Rector Magnificus, dr. E. Sterken,
in het openbaar te verdedigen op
donderdag 15 november 2012
om 12.45 uur

door

Anne Johannes Jan Braaksma

geboren op 25 februari 1980
te Leeuwarden

Promotores:	Prof. dr. ir. J.C. Wortmann Prof. dr. ir. G.J.C. Gaalman
Copromotor:	Dr. ir. W. Klingenberg
Beoordelingscommissie:	Prof. dr. B. Iung Prof. dr. H. van Landeghem Prof. dr. R. Teunter

ISBN: 978-90-367-5806-2 (book)
978-90-367-5807-9 (e-book)

Contents

Chapter 1

Introduction

This chapter includes a motivation for the research presented in this thesis (1.1), a description of the industrial setting in which the research takes place (1.2), the research aim (1.3), the research objectives (1.4) and the outline of this thesis (1.5).

1.1 Motivation of the study

Reliability, safety and sustainability of capital assets is of major importance to our society. Maintenance has an important role in assuring the integrity of assets and thereby in assuring the reliability, safety and sustainability of these capital assets (Moubray, 1992). The importance of Maintenance (MRO, Maintenance Repair and Overhaul) is also represented by a yearly turn-over of 18 billion euro and employment for around 300.000 people which is 4% of the working population in the Netherlands (NVDO, 2011). The total value of the Dutch capital assets is being estimated at 400 billion euros (Veenman and Besselink, 2010). Plant maintenance is therefore a major operational activity, the cost of which typically represents some 4% of the capital employed, in the process industry this can be 6% (Haarman and Delahay, 2005).

Maintenance concepts

Given the significance of maintenance for operational excellence as well as health, safety and environment, the importance of a good maintenance concept is paramount. A maintenance concept can be seen as the policy, or the approach that governs the amount of maintenance and type of maintenance actions to be performed on an asset. For example, the maintenance concept determines the choice between planned maintenance with fixed intervals or planned maintenance with variable intervals for an asset.

Asset definition

In the remainder of this thesis, the terms plant/ installation, equipment and products are grouped under the term ‘asset’.

For asset management we use the definition of Mitchell and Carlson (2001), *cited in* Schuman and Brent (2005), where asset management is defined as a strategic, integrated set of comprehensive processes to gain greatest lifetime effectiveness, utilisation and return from physical assets, whereby assets are defined as production and operating equipment and structures.

The maintenance concept of an industrial asset is nowadays seen as an essential part of the design (phase) of the asset (Dongen, 2011), but can also be determined or improved in the operations and maintenance phase of an asset. The importance of a life-cycle approach to the design, management and continuous improvement of assets is well described (INCOSE, Dreverman, 2005, Schuman and Brent, 2005).

Maintenance and asset information

Only with effective maintenance the assets continue to do what the users want them to do (Moubray, 1992). An important aspect in determining the maintenance concept is the information that is available and how this asset information is used.

Some authors mentioned a number of problems with the information management in a maintenance environment:

1. *uncertainty of future information needs:* it is unclear which data has to be registered or maintained for future asset management (Tsang *et al.*, 2006, Veldman *et al.*, 2010),
2. *maintenance knowledge is insufficiently accessible:* much of the information is embodied in persons (Moubray, 1992, Mobley and Smith, 2002, Bloom, 2006),
3. *information cannot be used without additional knowledge:* asset data is stored without sufficient context to be interpreted correctly and used effectively, (Pot, 2007, Tsang *et al.*, 2006, Teoh and Case, 2005),
4. *maintaining high quality asset data is complex and costly*: the quality of asset information is difficult to establish, which is further complicated by often terabytes of data which need to be maintained (Garg and Deshmukh, 2006, Tsang *et al.*, 2006),
5. *heterogeneity of storage applications:* data is stored in several non-integrated systems, e.g. Computerized Maintenance Management Systems (CMMS), process data and RCM data which complicates analysis which needs several data sources (Garg and Deshmukh, 2006, Smith and Hinchcliffe, 2004, Haarman and Delahay, 2005).
6. *data hand-over problems:* the breaking-point (caused by the hand-over) of asset data between maintenance and engineering (Dreverman, 2005)
7. *lack of information standards:* which complicates the exchange of asset data (Dreverman, 2005).

Reliability Centred Maintenance (RCM)

Reliability Centred Maintenance (RCM) is currently seen by many authors as an important approach to design /develop a maintenance concept (Moubray, 1992, Mobley and Smith, 2002, Waeyenbergh and Pintelon, 2002, Stamatis, 2003, Bloom, 2006, Seyed-Hosseini *et al.*, 2006). RCM also described in the SAE JA1011 standard starts with a zero-based review to determine the maintenance requirements of any physical asset in its operating context (Moubray, 1992).

RCM was developed over a period of thirty years, its origins go back to a report commissioned by the US department of Defense describing the application of RCM in the civil aviation industry (Nowlan and Heap, 1978). The application of RCM forms a basis for preventive maintenance activities and can therefore influence a significant part of the operational expenses.

A very important aspect of the RCM methodology is Failure Mode and Effect Analysis (FMEA). FMEA was developed in 1949 by the American Army to evaluate the impact of system and equipment failures on mission success and the safety of personnel and equipment (Teoh and Case, 2005). FMEA can be defined as “a method of reliability analysis intended to identify failures affecting the functioning of a system and enable priorities for action to be set” (BS5760, 2009). The FMEA method is a qualitative assessment of risk, predominantly relying on the judgment of experts (Moubray, 1992).

By performing FMEAs, failure modes are identified. Failure modes are the ways, or modes, in which an asset can fail. The severity, probability of occurrence and risk of non-detection are estimated and used to rate the risk associated with each failure mode. Usual practice is to combine these elements in a ‘risk priority number’ or RPN (Dieter, 2000). Three factors are usually taken into account when evaluating the risk of failure: the severity; the probability of occurrence; and the likelihood of detecting the failure (Dieter, 2000, Stamatis, 2003).

FMEA can be performed in various phases of the life-cycle. Depending on the object of study they are called (1) system FMEA, (2) design FMEA, (3) process FMEA and (4) service FMEA (Stamatis, 2003). For this PhD thesis we focus on the service FMEA.

The relationship between RCM and FMEA is illustrated in figure 1.1, amended from Picknell (1999). Part II, is the FMEA part of the RCM analysis. The end result of an FMEA is used as input to make a RCM based decision (Part III) which determines the optimal maintenance policy of an asset (part). Assessments and decisions taken within FMEA (Part II) therefore heavily influence the RCM decisions and thus the quality of the maintenance concept.

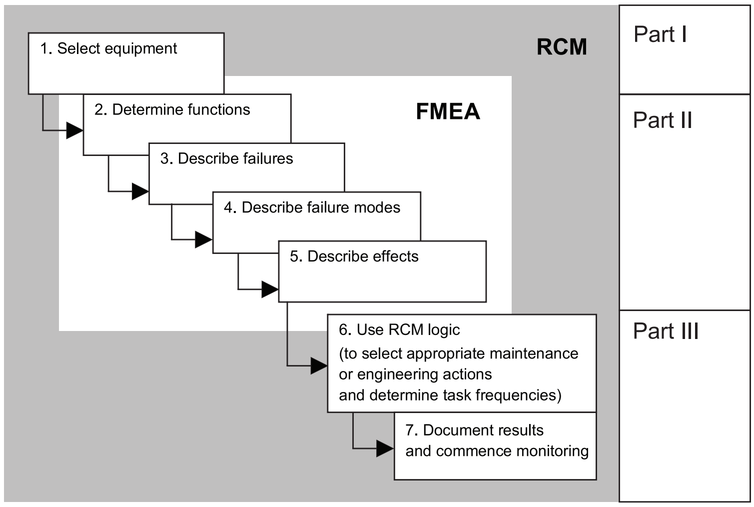

Figure 1.1: FMEA as part of the RCM process, amended from Picknell (1999)

Important parts of the RCM/FMEA process but not depicted in the above figure is the context in which the RCM/FMEA process is conducted: the selection and composition of the RCM/FMEA team and the chosen level of analysis (e.g. on system, subsystem or component level).

1.2 Feedback is essential for FMEA-based maintenance

According to seminal authors, feedback is essential for the success of a living FMEA and an effective and efficient maintenance program (Bloom, 2006, Teoh and Case, 2005, Moubray, 1992). The FMEA is however not reviewed or updated anymore after its initial use (Braaksma *et al.*, 2012a, Teoh and Case, 2005, Teng and Ho, 1996). In other words, FMEA is regarded as a one-time only exercise: not as an object of development (Braaksma *et al.*, 2011).

Because of the importance of asset information, asset information management can be viewed as enabler of feedback on FMEA and thereby as a precondition for continuous use of FMEA for maintenance improvement.

Therefore, the preventive maintenance plan might be inaccurate when used in practice. It is difficult to assess the exact impact of the inaccuracies, but it is likely that they will lead to unnecessary costs.

Accordingly, this thesis aims to study the possibilities to improve asset information management in order to allow feedback in FMEA-based maintenance.

1.3 Industrial setting

In the following paragraphs the support of Stork Technical Services, USPI-NL and the focus on the process industry are discussed.

1.3.1 Stork Technical Services

Stork Technical Services, supported the research presented in this thesis. Stork Technical Services is actively engaged in maintenance management and is constantly evaluating and improving their (maintenance) practices. As a large Dutch maintenance contractor Stork Technical Services is responsible for the maintenance of often large complex, capital-intensive physical assets such as buildings and industrial plants.

Stork Technical Services has in-depth asset management expertise built up by many years of experience and cooperates with world class corporations within Chemical, Oil, Gas and Power industries. Stork Technical Services has in-depth asset management expertise in, Project Management Services, Maintenance Management Delivery, Turnaround Management, Relocations and Brownfield Engineering.

One of the frequently used tools Stork Technical Services is using for the improvement of maintenance concepts of their customers is FMEA or Failure Mode and Failure Mode Effects and Criticality Analysis (FMECA). Stork Technical Services therefore expects to benefit from (academic) knowledge resulting from detailed analyses on asset information management.

1.3.2 USPI-NL

USPI-NL, a formal Association of process industry actively supported the research presented in the thesis. The mission of USPI-NL is to develop, promote and maintain international asset information standards and best practices for the process industry plant engineering supply chain. Key standards actively supported today are ISO 15926, ISO 8000, STEP/ISO10303, NE100 for product and plant life cycle information. Best practices cover As-built information and Specification of handover information in the plant supply chain.

The plane engineering life cycle phases range from design to maintenance and finally demolition of the plant. USPI-NL is therefore also interested in the engineering knowledge about the use of international standards and practices, currently with a particular focus on maintenance knowledge management.

1.3.3 Focus on the process industry

This study focuses on the process industry, which has some specific characteristics when compared to other industries: (1) the need to use complex and expensive installations efficiently and safely (Fransoo and Rutten, 1994, Dennis and Meredith, 2000, Hu *et al.*, 2009), (2) the design of the plant and equipment tends to be important for safety and operational performance when compared to other industries (Gunasekaran, 1998) and (3) Structured preventive maintenance, including the use of FMEA, is therefore important for companies in the process industry (Azadeh *et al.*, 2010).

Because of the aforementioned importance of good structured maintenance in the process industry and since the process industry is one of the strategic focus areas of Stork Technical services we concentrated our research on the process industry.

1.4 Research aim

As we described the importance of maintenance and more specifically the importance and current problems with information management in a maintenance context,

the research aim of this thesis is to contribute to the academic knowledge on asset information for FMEA-based maintenance management.

1.5 Research objectives

To achieve the research aim we identified several research objectives. Each research objective has a main research question which is described in the following paragraphs.

1.5.1 Failure Mode and Effects Analysis in asset maintenance: a multiple case study in the process industry

FMEA is an important method for determining maintenance programs. However, there has not been much empirical research on the actual use of the method. The aim of the first research question below is to examine whether common assumptions found in literature on Failure Mode and Effects Analysis (FMEA) and its use for (preventive) maintenance can be supported by empirical evidence and to explore reasons why companies would deviate from what is generally assumed in the literature. A multiple case study design is applied for theory-building from an exploratory perspective (McCutcheon and Meredith, 1993, Meredith, 1987). Exploratory research is applicable when researchers have no solid ideas on the exact behavior and causal relationships of the concepts in practice. In the multiple case study, we aim to develop knowledge that can serve as a stepping stone towards such theory building (McCutcheon and Meredith, 1993, Meredith, 1987).

RO1: To what extent are common assumptions on the use of Failure Mode and Effects Analysis for (preventive) maintenance supported by empirical evidence?

1.5.2 A quantitative method for Failure Mode and Effects Analysis

In literature it has been reported, that despite its popularity, the FMEA method lacks the repeatability and the ability to continuously improve maintenance routines (Teoh and Case, 2005). There is a need for a quantitative method which enables the probability of asset failure to be expressed as a function of explanatory variables, such as age, operating conditions or process measurements. Our aim is therefore to develop a quantitative method which improves the repeatability of the FMEA for the purpose of asset maintenance.

RO2: How can the repeatability of the FMEA method be improved and how can the ability to continuously improve maintenance routines be developed?

1.5.3 Design of a Maintenance Feedback Analysis (MFA) method for continuous FMEA-based maintenance

Failure Mode and Effects Analysis (FMEA) is an important method to design and prioritize preventive maintenance activities. Within a reliability-centred maintenance used as a basis for preventive maintenance planning (Moubray, 1992, Bloom, 2006). The FMEA is however not reviewed or updated anymore after its initial use (Braaksma *et al.*, 2012a, Teoh and Case, 2005, Teng and Ho, 1996) when it is been hand-over from design engineering to maintenance engineering as part of a larger maintenance program. However, according to seminal authors, information feedback is essential for the success of a living FMEA and an effective and efficient maintenance program (Bloom, 2006, Teoh and Case, 2005, Moubray, 1992). The aim of our third research objective is therefore to explore the context for feedback in maintenance strategies, and to come up with requirements and design principles which can be used for a method which enables information feedback.

RO3: What are requirements and design principles for continuous FMEA-based maintenance?

1.5.4 A review of the use of asset information standards for collaboration in the process industry

For effective asset information management and continuous FMEA-based maintenance management there is presumably a need for all data and information of the installation to be up-to-date, consistent and complete. Successful exchange of asset design information between disciplines and parties is therefore a prerequisite for the success of the optimization processes in later life-cycle phases. Fragmentation of the information management processes and the information sources can lead to failure in terms of data integrity. Asset information standards are believed to enable effective information management, however asset standards adoption is lacking pervasiveness in the process industry. In order to investigate other possible causes for lack of adoption, as well as possible solutions, a comparison is sought with other industries, in which asset information standards are important (and important progress was made): the aerospace industry and automotive industry.

RO4: What are the causes for the lack of pervasiveness of asset information standards in the process industry compared to the aerospace industry?

1.6 Thesis outline

In the next four chapters, an investigation into FMEA-based maintenance improvement and related aspects of this theme are reported:

(i) the use of FMEA for asset maintenance in the process industry: chapter 2 summarizes the main descriptions and assumptions found in the literature on FMEA into six postulates, and compares the postulates to industrial practice,

(ii) a quantitative method to support Failure Mode and Effects Analysis: chapter 3 proposes an enhancement to the FMEA method which enables the probability of asset failure to be expressed as a function of explanatory variables, such as age, operating conditions or process measurements. The probability of failure and an estimate of the total costs can be used to determine maintenance routines. The procedure facilitates continuous improvement as the dataset builds up,

(iii) the design of a Maintenance Feedback Analysis (MFA) for continuous FMEA-based maintenance: chapter 4 presents the design of a Maintenance Feedback Analysis method (MFA) extending the RCM/FMEA approach. The aim of MFA is to improve FMEA related information management for continuous use of RCM/FMEA logic.,

(iv) the use of asset information standards for the exchange and storage of asset information: chapter 5 reviews the use of asset information standards for collaboration in the process industry this is based on a survey of the literature and two case studies in which a comparison with the aerospace industry is made.

Publication of chapters in journal articles
The chapters included in this thesis are based on journal articles that either published, or are under review by a journal. The following articles are included in this thesis:

Chapter 2 – Braaksma, A.J.J., Klingenberg, W., Veldman, J., 2011, Failure Mode and Effects Analysis in asset maintenance: a multiple case study in the process industry, *International Journal of Production Research*, in press.

Chapter 3 – Braaksma, A.J.J., Meesters A.J., Klingenberg, W., Hicks, 2011, C., A Quantitative method for Failure Mode and Effects Analysis, *International Journal of Production Research,* in press.

Chapter 4 – Braaksma, A.J.J., Wortmann, J.C., 2011, Design of a Maintenance Feedback Analysis (MFA) method for continuous FMEA-based maintenance. In process of submission to International Journal of Production Research.

Chapter 5 – Braaksma, A.J.J., Klingenberg, W., Exel, P.W.H.M van, 2011, A review of the use of asset information standards for collaboration in the process industry, *Computers in Industry*, Volume 62, Issue 3, Pages 337-350.

Finally, **Chapter 6** includes a summary of the main findings, future research directions and a discussion on the societal relevance of the research.

Chapter 2

Failure Mode and Effects Analysis in asset maintenance: a multiple case study in the process industry

Failure Mode and Effects Analysis (FMEA) is an important method to design and prioritize preventive maintenance activities and is often used as the basis for preventive maintenance planning. Although FMEA was studied extensively, most of the published work so far covers FMEA concept design. Not much detailed comparison to industrial practice regarding the application of FMEA can be found in the literature, which is the contribution of this study. This chapter summarizes the main descriptions and assumptions found in the literature on FMEA into six postulates, and compares the postulates to industrial practice. This was done in a multiple case study conducted at six companies in the process industry. Some postulates were supported by empirical evidence, whereas for others, limited or no support could be found. The results suggest a fundamental problem in the FMEA procedure, namely the reliance upon expert judgment in general and the reliance upon design engineering expertise for keeping the FMEA up-to-date in particular. Also a number of operational and information management problems that companies suffer from when conducting an FMEA were identified. Practitioners can use this chapter to assess their potential for implementing FMEA and to learn from the insight into the identified pitfalls. Researchers can use the findings to guide further work on improving and developing the FMEA procedures.

2.1 Introduction

Plant maintenance is a major operational activity in the process industry, the cost of which typically represents some 4% of the capital employed (Veenman and Besselink, 2010). Preventive maintenance is an important element of plant maintenance. Several authors have described Reliability-centered maintenance (RCM) and Failure Mode and Effects Analysis (FMEA) as an important method to define preventive maintenance programs (Bloom, 2006, Waeyenbergh and Pintelon, 2002, Mobley and Smith, 2002, Stamatis, 2003, Seyed-Hosseini *et al.*, 2006, Moubray, 1992) and this was also witnessed by the current authors. The application of RCM/FMEA therefore forms a basis for the preventive maintenance activities and influences a significant part of the operational expenses. This chapter examines how the RCM/ FMEA method is applied in practice and whether a number of common assumptions found in the literature on the way RCM/FMEA programs are implemented can be supported by empirical evidence.

2.1.1 Failure Mode and Effects Analysis (FMEA)

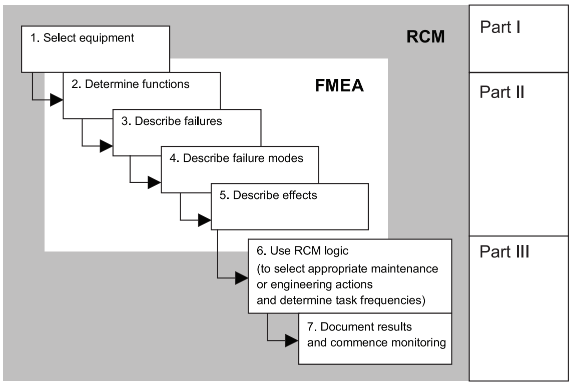

Figure 2.1: FMEA as part of the RCM process, amended from Picknell (1999)

FMEA is a method of reliability analysis intended to identify failures affecting the functioning of a system and enable priorities for action to be set (BS5760, 2009). FMEA is used to identify failure modes. Failure modes are the ways, or modes, in which an asset can fail. The severity, probability of occurrence and risk of non-detection are estimated and used to rate the risk associated with each failure mode. Usual practice is to combine these elements in a 'risk priority number' (Dieter, 2000). FMEA is an important part of Reliability-centered maintenance, defined by Moubray (1992, p.8) as a "process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context". The steps within RCM are shown in Figure 2.1 (Moubray, 1992, Picknell, 1999). The FMEA process has been adapted for use in many international standardized quality systems including IEC60812, QS9000 and ISO 9001.

Some authors have criticized the approach because it is said to be complex, time consuming and ignores existing barriers between asset management processes (Dow and Endersby, 2004, Gabbar *et al.*, 2003, Tsang, 2002). Nevertheless, the method is described as an important practice in asset management and presented as one of the key advanced maintenance methods (Bloom, 2006, August, 2003, Moubray, 1992).

The current literature predominantly covers progress in FMEA process and concept design, in which implicit or explicit assumptions are made regarding the use of FMEA in maintenance planning in practice. However, detailed comparison of the practical use of the FMEA procedure in industry has not received as much attention yet. We have searched the International Journal of Production Research; Journal of Quality in Maintenance Engineering; Reliability Engineering & Systems Safety; International Journal of Operations & Production Management; International Journal of Production Economics and Computers in Industry among others, and were not able to identify a broad study comparing the descriptions in the academic literature to industrial practice.

2.1.2 Aim and scope

The aim of this chapter is to help fill that gap by examining whether a number of common assumptions found in the literature on Failure Mode and Effects Analysis (FMEA) and its use for (preventive) maintenance can be supported by empirical evidence and to explore reasons why companies would deviate from what is generally assumed in the literature. We will do so by conducting a multiple case study.

Our study focuses on the process industry. According to the American Production and Inventory Control Society (APICS) process production is defined as: "production that adds value to by mixing, separating forming, and/or chemical reactions" (Cox and Blackstone, 1995). Process industries are characterized by the need to use complex and expensive installations efficiently and safely (Fransoo and Rutten, 1994, Dennis and Meredith, 2000, Hu *et al.*, 2009). Capital investments tend to be high and expenses for downtime tend to be large, which puts pressure on the maintenance function and causes the need for sophisticated maintenance procedures (Tan and Kramer, 1997, Arts *et al.*, 1998, Gunasekaran, 1998, Ketokivi and Jokinen, 2006, Veldman *et al.*, 2011). Structured preventive maintenance, including the use of FMEA, is therefore important for companies in the process industry (Azadeh *et al.*, 2010).

The chapter is organized as follows. The chapter starts with an explanation of the methodology in Section 2. In Section 3, our theoretical framework is presented. The theoretical framework consists of six postulates that are based on the main descriptions and assumptions found in literature is presented. The postulates are structured according to the three phases within the RCM/FMEA process. Section 4 presents the multiple case study and the comparison of the postulates to industrial practice in the process industry. The chapter ends with the discussion and conclusions in Section 5.

2.2 Methodology

Our primary aim is theory-building from an exploratory perspective (McCutcheon and Meredith, 1993, Meredith, 1987). The research is exploratory since we have no solid ideas on the exact behavior and causal relationships of the concepts in practice and we aim to develop knowledge that can serve as a stepping stone towards such theory building (McCutcheon and Meredith, 1993, Meredith, 1987). The confirmation or disconfirmation of conceptual insights found in the literature is organized around a set of postulates. The term 'postulate' is used for a commonly accepted truth and serves as a starting point for deducing and inferring other (theory dependent) truths. For this study it is appropriate to use a multiple case study (Eisenhardt, 1989, Yin, 1994, Dul and Hak, 2008, Eisenhardt and Graebner, 2007). At a more detailed level the methodology we follow is very similar to that of Meredith (1987) and Veldman et al. (2011).

2.2.1 Sample selection

Our sample consists of six companies in the process industry. The number of cases exceeds the minimum number of four required for multi-case research (Eisenhardt, 1989). Case selection based on a set of specific criteria is considered important in case research (Eisenhardt and Graebner, 2007, Siggelkow, 2007). The criteria employed for case selection are (also see Veldman et al., 2011):

(1) Company size, whereby companies were selected with a minimum number of employees of 50. This is based on the assumption that larger companies have more resources and other possibilities for the development of advanced maintenance routines, including Failure Mode and Effects Analysis (Azadeh *et al.*, 2010);
(2) The degree to which the companies consider plant maintenance as an important area for achieving excellent overall performance. This was measured by interviewing key personnel prior to the actual case study;

(3) In addition, a selection was made of companies that are not carrying out maintenance activities on the same assets and that do not have a direct supply relationship, in order to avoid any 'double dipping'.

At six case companies, interviews were conducted with relevant staff, including maintenance manager(s) and reliability engineer(s) (see below). Follow-up telephone interviews were used for validation. The interview data was structured and labeled per company to allow for cross-case analysis. Additional data sources included written documents and presentation material. Measures taken to ensure the validity and reliability are summarized in Table 2.1 (Yin, 1994).

Criterion	Implementation
Construct validity	Multiple documents, multiple informants, informants were asked to provide additional information in follow-ups
Internal validity	Pattern matching using cross-tabulations, careful attention for rival explanations; both theoretical as well as in interview protocol
External validity	Selection of case companies typical for process industry, use of authors' expert opinions on uniqueness of case companies
Reliability	Structured interview protocol, careful write-up of interview data

Table 2.1: Ensuring validity and reliability

2.2.2 Interview protocol and data collection

To maintain consistency in the data from each company, we used a structured interview approach and used a tape-recorder to make transcriptions if this was allowed by the interviewee. The interviewer used the same interview protocol to gather data for the study. The protocol was pre-tested to make sure that the questions were sufficiently clear. At each company, the interviewer met with the maintenance manager(s), reliability engineer(s) and other interviewees who were in some cases contracted from a specialized company. Interviewees were selected based on in-depth knowledge of the company, the assets, the way FMEAs were conducted and used for subsequent maintenance planning and the use of support systems. After the interviews, the reports were validated by the interviewees.

2.3 Postulates

In this section, we will summarize the current assumptions and descriptions of FMEA found in the literature into six postulates.

2.3.1 Introduction

In this section we present the postulates that are based on a comprehensive review of the current literature on FMEA and its use in asset maintenance. The postulates basically cover the steps of RCM as also shown in Figure 2.1. We have divided the RCM/FMEA process into three parts: (i) the identification and selection process (step 1), (ii) the actual FMEA process (steps 2 to 5), and (iii) the derived actions (steps 6 and 7). Careful attention to each of these three parts is of paramount importance (Moubray, 1992, Mobley and Smith, 2002, Smith and Hinchcliffe, 2004, Bloom, 2006). We will therefore propose postulates for each of the three parts.

2.3.2.1 RCM/FMEA identification and selection process postulates (Part I)

This section describes postulates on the use of Failure Mode and Effects Analysis within RCM, with regard to the identification and selection of assets to be analyzed with FMEA as this is the first step in Failure Mode and Effects Analysis (Moubray, 1992, Bloom, 2006, Riezebos *et al.*, 2009).

Postulate 1: *Failure Mode and Effects Analysis is applied on a limited selection of assets*

In the recent literature, it is generally assumed that a limited number of assets for RCM/FMEA are to be selected, for instance assets that are critical to safety and plant performance (e.g. Bloom, 2006, Waeyenbergh and Pintelon, 2009, Rosqvist *et al.*, 2009, Smith and Hinchcliffe, 2004, Waeyenbergh and Pintelon, 2004). Moubray (1992, p.16) mentions that assets should be selected that 'most likely benefit from the RCM process' and to make clear how the asset parts will benefit from the RCM process. Bloom (2006, p.143) argues that all parts should be part of the analysis as vulnerabilities otherwise may stay unidentified.

An important assumption in FMEA and a prerequisite for identifying the assets is the existence of a plant register or maintenance database (Mobley and Smith, 2002, Moubray, 1992, Waeyenbergh and Pintelon, 2002, Tsang, 2002, Bloom, 2006, Gabbar *et al.*, 2003, Kans, 2008). Moubray (1992) explains that a plant register is required to identify the assets and their location and that the plant register should be designed in such a way that it is possible to keep track of the assets that have been analyzed, those that have yet to be analyzed and those that are not going to be used. This would include coding each asset uniquely and in such a way that selection and administration is fully supported. Asset information standards can be used for this (Braaksma *et al.*, 2011).

2.3.2.2 FMEA process (Part II)

This section describes postulates with regard to the accuracy and standardization of the FMEA process.

Postulate 2: *Failure modes and effects are identified with sufficient accuracy*

A failure mode can be defined as any event that is likely to cause a functional failure of an asset (Moubray, 1992). Failure modes can be classified into three categories: (1) when the capability falls below the desired performance, (2) when the desired performance rises above initial capability and (3) when the asset is not capable of doing what is wanted from the outset (Moubray, 1992).

Expected future failure modes are implicitly or explicitly assumed by many authors to be identifiable with considerable accuracy (Moubray, 1992, Mobley and Smith, 2002, Smith and Hinchcliffe, 2004, Down *et al.*, 2008). In particular, Moubray (1992 p.64) points out that failure modes should be defined in sufficient detail for selecting a suitable failure management policy. The literature proposes the identification of failure modes to take place through facilitated group sessions, bringing together knowledge and expertise (Moubray, 1992, Mobley and Smith, 2002, Smith and Hinchcliffe, 2004, Down *et al.*, 2008). The best sources of information according to (Moubray, 1992) are the people who operate and maintain the equipment. To support the process, information from industry databases and standards may be used (SINTEF, 2002, Azadeh *et al.*, 2010).

Failure effects can be defined as the consequences of each failure mode on operation, function or status of an asset (DoD, 1980). Moubray (1992) recognizes three types of consequences; safety and environmental, operational and non-operational consequences. A number of authors have assumed that the effects of failure modes can also be identified and described accurately (Moubray, 1992, Mobley and Smith, 2002, Smith and Hinchcliffe, 2004, Down *et al.*, 2008).

Postulate 3: *Failure Mode and Effects Analysis is applied according to a clearly defined paper- or software-based procedure*
FMEA procedures are described by a large number of authors (Stamatis, 2003, Moubray, 1992, McDermott *et al.*, 2009, Down *et al.*, 2008) as being highly structured and are implemented in numerous standards (e.g. IEC60812, QS9000, BS 5760, MIL-STD 1843 and ISO 9001). The importance of the structured nature of the approach is stressed by several authors (e.g. Bloom, 2006, McDermott *et al.*, 2009). The main advantages are that it provides a common language (McDermott *et al.*, 2009) and that it forces an organization to systematically evaluate equipment and system weaknesses and their interrelationships (Mobley and Smith, 2002).

The standardization and structure of FMEA is enhanced by tools supplied by software vendors. The University of Maryland (UMD, 2010) made a comprehensive list of more than 20 software packages. These software packages incorporate the use of FMEA standard procedures such as MIL-STD-1629, MIL-STD-1388, QS-9000 and SAE J1739 (UMD, 2010).

2.3.2.3 RCM logic application (Part III)

This section describes postulates on the selection of (appropriate) maintenance actions by using FMEA.

Postulate 4: *Following the FMEA method ensures consistency in maintenance decision-making, e.g. the design of maintenance routines and maintenance planning*
The result of conducting an FMEA procedure is to design preventive maintenance routines and planning (Mobley and Smith, 2002, Moubray, 1992, Bloom, 2006) as also visualized in Figure 2.2 (after Bloom, 2006).

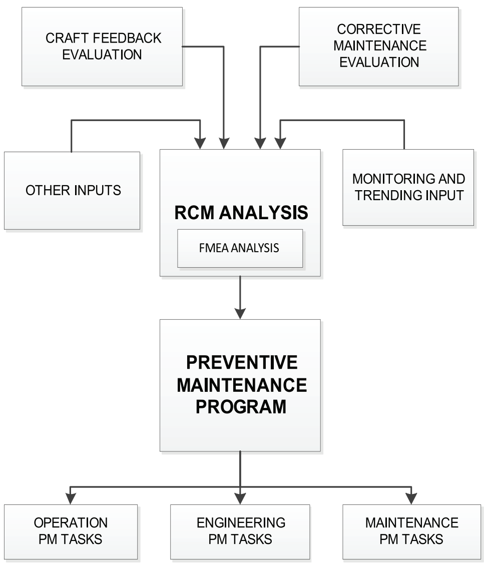

Figure 2.2: Relationship FMEA, RCM and maintenance planning (Bloom, 2006)

FMEA is generally seen as a method to ensure that the decisions are consistent, i.e. that the (priority in the) preventive maintenance actions clearly relate to the potential failure modes and effects, registered in plant records (Waeyenbergh and Pintelon, 2002, Moubray, 1992, Smith and Hinchcliffe, 2004, Bloom, 2006).

Postulate 5: *FMEA enables continuous improvement*

Various authors emphasize the importance of periodically or occasionally reviewing and improving the FMEA findings and conclusions, e.g. Moubray (1992), Bloom (2006), Down et al. (2008), Waeyenbergh and Pintelon (2002 p.307), and Stamatis (2003). Moubray (1992 p.316) states that an RCM/FMEA database (which is the result of a RCM review) enables “tracking the reason for every maintenance task right back to the functions and the operating context of the asset. As a result, if any aspect of the operating context changes, it is easy to identify the tasks which are affected and to revise them accordingly”.

Bloom (2006) states that the RCM/FMEA process must remain a ‘living’ one, never to become static. New failure modes may become evident, and additional information relative to equipment performance may present itself at any time. Oftentimes, the preventive maintenance schedule may need to be adjusted. Periodicities may need to be increased or decreased. Newly identified tasks may need to be added, while others may need to be deleted based on new or different operating conditions or plant modifications. A living program includes a feedback loop, which is important because it helps to maintain the viability of the program (Bloom, 2006). Down et al. (2008 p.63) explain that the focus should always be on continuous improvement: “After the preventive/corrective action has been completed, the (risk) priority indicator should be calculated again and revised rankings should be reviewed. If further action is considered necessary, then repeat the analysis”. Stamatis (2003 p.xxvii): “The push for this continual improvement makes the FMEA a dynamic document, changing as the system, design, process, product, and/or service changes”.

Postulate 6: *FMEA relies predominantly on expert judgment. The use of historic failure data or other measured data is generally not possible for conducting an FMEA.*

It is argued in the literature that it may not be worthwhile to look at historic data. This is because most historic data and records are assumed to be of insufficient quality for this purpose (Moubray, 1992, Smith and Hinchcliffe, 2004, Garg and Deshmukh, 2006). Moubray (1992) mentions the following problems: (1) the data/records are often incomplete,

(2) more often than not, the data/records describe what was done to repair the failure rather than what caused it, (3) they do not describe failures which have not yet occurred and (4) they often describe failure modes which are really the effect of some other failure. In addition, the use of quantitative optimization models (employing historic data) is considered very limited in industry (Garg and Deskmukh, 2006).

Therefore the reliance on expert judgments is advocated in the FMEA literature, Moubray (1992 p.17): "many (if not most) of the answers can only be supplied by production or operations people. This applies especially to questions concerning functions, desired performance, failure effects and failure consequences". (Bloom, 2006 p.19) states that it takes the cumulative knowledge from all associated parties to affect a premier analysis but does recognize other sources of information.

2.4 Multiple case study

First we will briefly introduce the case companies, after which we will discuss the results of the multiple case study.

2.4.1 General case company descriptions

1 is a consortium of companies, delivering engineering, renovation and maintenance services for a series (>5) of fossil fuel production facilities of a major energy company.
2 produces various fillers and cleaning chemicals. The production process consists mainly of mixing and packaging processes. For our research we focus on the mixing processes. *2* is part of a major international chemical company.
3 provides custom contract manufacturing services to the pharmaceutical industries. We focus on one of the production facilities. 3 is part of a major international chemical company (different from *2*).
4 is an electricity producer. We focus on five power stations. The investigated power stations are traditional power station consisting of a boiler and a steam turbine connected to a generator. The plants investigated are coal and gas fired plants.
5 is a consortium of companies, delivering engineering, renovation and maintenance services for a series (>5) of fossil fuel production facilities of a major energy company. Companies *1* and *5* are not the same.
6 is a major producer of minerals for both industrial and consumer markets. The plant, on which we focus, is part of an international company in the minerals industry.

At a general level, the companies are comparable since that they are all (part of) major companies in the process industry with an international perspective. Access to knowledge on RCM/FMEA is sufficient and comparable across the case companies. Also the physical production technologies are comparable in the sense that they are all typical examples of the process industry, although the plants differ in age, asset heterogeneity, level of redundancy and size. Table 2.1 summarizes the case companies. As will become apparent in the discussion of the postulates, many of the findings are illustrated by quotes from the interviewees, who were usually very frank. For reasons of confidentially, we have named the six companies *(A)* through *(F)* during the discussion of the postulates, whereby the letters do not correspond to the numbers used in Table 2.2.

Company	**1**	**2**	**3**	**4**	**5**	**6**
Main output	Fossil fuel	Fillers and cleaning chemicals	Pharmaceuticals	Electricity	Fossil fuel	Minerals
Asset owner	No	Yes	No (group is owner)	Yes	No	Yes
# Plants	>5 production locations (various types)	1 production plant	1 production plant	5 electricity production plants (various types)	> 5 identical production locations	1 mineral production plant
Main equipment (per plant)	Fossil fuel processing equipment	Mixing equipment and packaging equipment	Bio reactor vessels, chillers, process (=fermentation) air compressors	Steam turbines, generators, steam condensers, machine transformer, kettle	Fossil fuel processing equipment	Boilers, condensers, centrifuges, packaging equipment
Object of analysis	Multiple FMEAs conducted in 1995 for initial maintenance plans and FMEAs carried out for new pieces of equipment.	Last FMEA conducted a year ago, FMEA every two years new equipment for the preventive maintenance program	FMEA recently (2009) conducted existing preventive maintenance program.	FMEAs conducted ten years ago for initial preventive maintenance program and FMEA at the time of study being conducted for two new plants	Ten FMEAs conducted during a ten-year period for planning preventive maintenance and prioritizing corrective maintenance.	FMEA conducted in 2010 and FMEA at the time of study being conducted as part of a new preventive maintenance program

Table 2.2: Case company backgrounds

2.4.2 Results

In the next paragraphs our research findings will be presented. Detailed additional information and a cross case overview can be found in Table 2.3.

2.4.2.1 RCM/FMEA identification and selection process postulates (Part I)

This section describes our empirical findings with regard to the formulated postulates on the RCM selection process (Part I in Figure 2.1).

Postulate 1: *Failure Mode and Effects Analysis is applied on a limited selection of assets/parts*

This postulate was confirmed during the case studies. Our finding was that all of the companies selected a limited number of 'critical' asset parts for RCM/FMEA, as other researchers have proposed (e.g. Bloom, 2006, Waeyenbergh and Pintelon, 2009, Rosqvist *et al.*, 2009, Smith and Hinchcliffe, 2004, Waeyenbergh and Pintelon, 2004). The reason for this is the resource intensity of the FMEA procedure, combined with the complexity of the assets. As a reliability engineer of (*B)* stated:

> "It is too much effort to conduct an FMEA on all parts of our installations. This would imply that e.g. 200.000 parts multiplied by a conservatively estimated time for analysis of 1 hour per part would yield approximately 100 man years of analysis work." (reliability engineer *B*)

Bloom (2006) described the risks of following an approach in which only critical assets are assessed. Interviewees at the case study companies commented that they are aware that some (small) risks might be taken by not including all assets in the scope of the FMEA, but that the required investment would be considered too large and the exercise unmanageable. As a reliability engineer of (*B)* stated:

> "We know that by not including all asset parts we take a risk but we have assessed these risks to be negligible. Besides the FMEA we also do other extensive analyses including HAZOP[1] and SIL[2] assessments." (reliability engineer *B*)

---

[1] Hazard and Operability (HAZOP) study (Summers, 1998)
[2] Safety Integrity Level (SIL) Assessment (Summers, 1998)

These findings are in line with recent literature on following a pragmatic approach in executing FMEA (e.g. Bloom, 2006, Waeyenbergh and Pintelon, 2009, Rosqvist *et al.*, 2009, Smith and Hinchcliffe, 2004, Waeyenbergh and Pintelon, 2004).

An important assumption made in the literature and a prerequisite for identifying the assets, is the existence of an asset register. In all of the companies an asset register[3] was used as a reference in identifying (parts of) assets for the FMEA. All companies used an internal coding standard, three companies based their coding on external standards i.e. the KKS[4] coding system, and the STEPlib[5] standard.

However, the policies for filling the asset register appeared to differ between companies. Some[6] companies made a first selection of critical parts when filling the asset register. This means that not all assets end up in the (maintenance) asset register. As a reliability engineer of (*B)* stated: "You only want assets in your register that you actually maintain". Others select from parts in the asset registry. As the FMEA facilitator of (*A)* stated:

> "The asset tree was already available in the asset register from the engineering phase. The existing tagging made it possible for us to identify and select the critical assets from the register. This selection depended upon the expected gains in terms of safety, production performance, environment/reputation and product quality. For (*A)* the highest impacts were expected in the first production stages, which therefore received most attention." (FMEA facilitator *A*)

The definition of 'critical' was based by all companies upon possible impacts on safety, environment, operational performance and quality. The selection of 'critical' assets was in all cases described as the outcome of a strategic (investment) decision process in which dominant stakeholders (the management of the firm, government (legislation) and maintenance management) play an important role. We tried to find quantitative criteria for the selection, we could however not find proof for the existence of such criteria.

---

[3] The asset register, as we called it in section 2.3.2.1., was called differently by each company. In most cases, it was named by the software vendor of the system, e.g. "The asset parts are registered in SAP.". In most cases, such a system contains more functionality than required for an asset register.
[4] The KKS Power Plant Classification System is a standardized system for the classification of power stations. It serves during engineering, construction, operation and maintenance of power stations for identification and classification of the equipment.
[5] STEP/ISO 10303 is an ISO standard for the computer-interpretable representation and exchange of product manufacturing information (Braaksma et al, 2011)
[6] Please see Table 2.3 for a detailed overview and cross case analysis.

A summary of the results regarding the first postulate on the selection of assets is given in Table 2.3.

Company	A	B	C	D	E	F
Extensiveness of selected assets for FMEA	only the most critical assets (FMEA program starting up)	first the most critical assets (business-case driven), afterwards also less critical assets	first the most critical assets (business-case driven), afterwards also less critical assets	most critical assets	most critical assets	most critical assets
Point at which selection of assets for FMEA was made (life-cycle)	maintenance phase	engineering phase, afterwards FMEAs were extended	maintenance phase (old assets) engineering phase (new assets)	engineering phase	maintenance phase	engineering phase
Use of Internal/ external coding standards	yes/no	yes/yes (STEP/PLIB standard)	yes/ yes (KKS coding system)	yes/no	yes/no	yes/no
Mapping of maintenance register with Engineering & Design register	Only partial mapping	Almost all parts are mapped to the maintenance register	Extensive mapping	Extensive mapping	Partial mapping	Extensive mapping

Table 2.3: Selection of assets at the six case study companies

2.4.2.2 FMEA process postulates (part II)

This section describes our empirical findings with regard to the postulates on the FMEA process (Part II in Figure 2.1).

Postulate 2: *Failure modes and effects are identified with sufficient accuracy*

We could only find limited support for this postulate. The case study reveals that there are problems with the accuracy in identifying and describing failure modes. In fact, identifying the failure modes was described as one of the main challenges for conducting an FMEA. Identified problems include a lack of information on the actual or potential asset failure, which in turn lead to difficulties in making detailed distinctions between failure modes and identifying possible causes. As a reliability engineer of (*D)* stated:

> "During the expert sessions there is generally a lack of detailed information on the actual failure modes. In fact, such information is usually absent. This is partially due to the nature of FMEA: one is anticipating possible failures, not only analyzing past occurrences. In addition, past maintenance activities may have prevented us from gathering useful information on actual failure modes." (reliability engineer *D*)

Particularly in cases where only limited specific information on failure modes is available (as was generally the case in this study), the accuracy of the analysis seems to be largely related to the knowledge and experience of the experts involved. Also the FMEA facilitator has an important role. This can be concluded from the following statements:

> "It is easy to get bogged down in long lists of possible failure modes. A danger is that the potential failure modes are too theoretical. In the minds of people there is often no specific difference between the various failure modes. In the end the challenge is to identify a limited number of credible and specific failure modes, based on which maintenance actions can be identified." (reliability engineer *B*)

and

> "You have to keep asking, what is the real problem? By repeatedly asking simple questions you can find out what the problems are. Involvement of all people invited to the meeting is crucial and social skills are very important. For example you have to calm a manager, or encourage someone else, perhaps a knowledgeable engineer, who is not saying much." (FMEA facilitator *A*)

Naturally, it is difficult to assess the precise impact of the inaccuracies, but it is likely that they will lead to unnecessary costs, since the case companies showed a tendency to widen their safety margins and apply extra maintenance in case of inaccuracies or uncertainties in the analyses. Despite the inaccuracies, interviewees replied that the identification of failure modes was sufficient ground for the remainder of the FMEA procedure.

With regard to the effects of the failure modes, the following challenges were found to be significant: (1) Effects are often described in a qualitative way. The quantification of effects was not always attempted, which led to problems in determining the level at which preventive action is necessary; (2) The relevance of the effects of failure modes may change over time due to changing circumstances, whereas the findings and subsequent maintenance activities are usually not adjusted; (3) The FMEA results were not stored in a way that made them suitable for constant updating. Moreover, the FMEA procedure was treated as a one-off exercise by four of the six companies. This aspect is also covered by Postulates 5 and 6.

The consequences of the combination of aspects (2) and (3) – the FMEA procedure is treated as a one-off exercise while circumstances change – are illustrated by:

> "Often there is a historic background which is relevant in the analyses. Sometimes this background is no longer valid. For example; we use a certain pipeline protection system designed for high pressure. Over time, the applied pressure is lowered. However, the special safety systems are still being inspected and maintained as if the pressure was very high, while in reality that is not the case anymore." (Focal point maintenance *D)*

Postulate 3: *Failure Mode and Effects Analysis is applied according to a clearly defined paper- or software-based procedure*

We could only find limited support for this postulate, because we found that some companies do apply FMEA in a fairly structured way, but others do not. Also the use of software tools and asset information standards (also discussed in Braaksma et al., 2011) is not always as structured as the literature suggests. For the companies that do follow a structured approach, the procedure is supported by clear corporate guidelines and/or structured software and/or by the coordination of a person managing the steps in the procedure. In some cases the abstraction level at which corporate guidelines for FMEA were defined appeared to be inadequate. For example at *B* and *F* corporate guidelines do require the execution of FMEA, but not define the procedure or the required steps to implement FMEA. This led to the use of different risk estimation methods and criteria within the same company.

Using standard software is seen by some as a good way to comply to the predefined steps in the FMEA procedure, whereas by others, this was seen as less important and the emphasis was placed on other aspects:

> "The SAP system or other software systems are not that important. We use a simple spreadsheet into which it is easy to copy the asset structure. It is more important to have an active chairman who leads the sessions in a structured way." (FMEA facilitator *A)*

A summary of the postulate regarding the FMEA process (part II) is given in Table 2.4.

Company	**A**	**B**	**C**	**D**	**E**	**F**
Extent to which available expertise and information was sufficient for identification	primarily expert knowledge and some maintenance history, sufficient for initial program, some expertise was missing	primarily expert judgment and supplier information	primarily expert judgment, some maintenance history, sufficient for an initial program	primarily expert judgment and supplier information	primarily expert knowledge, maintenance history, depending on age and supplier of equipment, own expertise compensates lack of supplier information	primarily expert knowledge, depending on equipment type, information was sufficient for FMEA, involvement of local expertise could have been more extensive
Extent to which uncertainties on Failure mode identification are being registered	as notes in FMEA report	as notes in FMEA report and also separately in personal notes	as notes in FMEA report	as notes in FMEA report, personally maintained notes added to FMEA spreadsheet	centrally maintained information system, not FMEA related spreadsheets	personally maintained notes, not FMEA related
Extent to which company guidelines or procedures force the organization to systematically evaluate current equipment with FMEA	no guidelines, use of custom spreadsheet based on FMEA standard	some implicit guidelines and procedures, use of custom spreadsheets and FMEA db tools (different FMEA standards)	only for new assets clear guidelines, use of custom spreadsheets (old assets), use of one standard for central FMEA db (new assets)	some implicit guidelines and procedures that make sure that FMEA is used, custom spreadsheets based on FMEA standard	no explicit guidelines or procedures, use of custom spreadsheet	company guidelines that prescribe the use of FMEA, use of custom spreadsheets and various FMEAdb tools

Table 2.4: Failure mode and effects process at the six case study companies.

2.4.2.3 RCM logic application (Part III)

This section describes our empirical findings with regard to the postulates on the application of RCM logic (Part III in Figure 2.1).

Postulate 4: *Following the FMEA method ensures consistency in maintenance decision making, e.g. the design of maintenance routines and maintenance planning*

We could not find sufficient support for this postulate, because we found that the FMEA procedure was in four out of six cases executed as a one-off exercise, after which changes were usually made to the preventive maintenance plan without reference to the original FMEA assumptions and outcome. An important reason is that the knowledge involved in the FMEA is usually tacit and documentation is scarce or distributed across a number of locations and systems. One important complication is that the original FMEA tended to involve design and process engineers and further optimizations to the maintenance plan are carried out by maintenance engineers. These two disciplines were usually not in close contact, for e.g. the simple fact that the design engineers were usually only or mostly involved during the design stage of the asset life cycle. This aspect also affects Postulates 6 and 7 and appears to be quite a fundamental problem in the FMEA procedure. One of the interviewees confirmed:

> "If we get feedback from the maintenance people in the field that maintenance practices can be improved we use this feedback to update the maintenance routines and change the planning in our maintenance management system." (Team leader maintenance *C*)

Another interviewee described the difficulty of tracing back the original FMEA decision making:

> "We tried to ask the experts who were involved in the original FMEA sessions ten years ago. If we were able to contact them, in most cases they could not provide the required insights as they could not recall the exact details and rationale behind their decision making." (reliability engineer *B*)

Also a lack of integration between the asset register, the maintenance management system and the FMEA software tools being used poses a problem for maintaining consistency, because information was stored at different aggregation levels in terms of the bill of material, and information had to be kept up-to-date in more than one place.

The absence of consistency between the FMEA assumptions and findings and the actual maintenance planning can lead to some failure modes unnecessarily receiving abundant attention, which may lead to excessive maintenance cost, or insufficient attention, which may lead to unnecessary risk. However, we have not witnessed any direct evidence of that.

Postulate 5: *FMEA enables continuous improvement*
We could only find limited support for this postulate, since at four of the six companies, the FMEA was primarily treated as a one-off exercise. Thereafter, other maintenance routines are being used, such as e.g. Root Cause Analysis (RCA) (Wilson *et al.*, 1993). The difference is quite fundamental: RCA is in principle reactive in nature, while FMEA aims to be pro-active, before a failure is occurring. One example:

> "The FMEA provides us with the original maintenance program. Thereafter, we solve the operational problems by conducting Root Cause Analyses based on problems that we have encountered in the field. People are flown in to help and analyze to see what happened and what has gone wrong." (Maintenance focal point *D*)

The fact that operational problems are solved using Root Cause Analyses does not remove the risk of having a sub-optimal maintenance plan, since this plan is still based on the original FMEA. Oftentimes, the solutions implemented after an RCA result in a change to the design of the installation (engineering change) or a local improvement of the maintenance routine, rather than a broad optimization of the maintenance plan. In addition, the original FMEA findings may become out-of-date if they are not maintained in subsequent RCA and other activities.

In summary, difficulties in enabling continuous improvement using FMEA are:
(1) The inability to re-access the expertise applied in the original FMEA procedure due to e.g. the design and process engineers only being present in this early phases of the asset life cycle;

(2) Use of other maintenance routines, such as Root Cause Analysis, and ad-hoc changes to the maintenance plan, whereby the original FMEA findings are not updated, rendering them out-of-date;

(3) Absence of (the use of) standards describing the FMEA procedure and output, so that consistent repetition is difficult, as was described earlier. Also various information management problems were identified, e.g. (a) Insufficient detail in the reports of the original FMEA. In one case, current users only received the result of the procedure (i.e. the maintenance planning) whereby the assumptions and analyses were lost. (b) Limited integration between the register used for the FMEA and other information systems containing asset information, hindering the use of all information necessary for the analysis. (c) The use of different FMEA databases/systems for the same purpose. (D) not all users were allowed access to the systems required for FMEA. (e) The FMEA procedure does not consider the prior existence of a maintenance planning. The value of existing practices can therefore potentially be underestimated.

At two companies we did find some evidence of improvements made to the original FMEA results. (*B)* did update FMEA findings at some point. This was possible because of the presence of design and process engineers within the organization at that time (team integration). Also *(E)* was showing efforts of updating the findings:

> "Of 50% of our assets we know the maintenance history, we store the maintenance findings in individual MS-Office files and we use this to review our maintenance plans. We are working towards the implementation of a central maintenance management system and we are also trying to extend this to all our assets. After every large revision we review what we have done and ask questions like: What did you see? What should we do next time? What was easier than expected and what was more difficult than we thought it would be. We always do this in the same consistent way and take some time for every piece of equipment." (Reliability Engineer *E*)"

However, for most companies, 'continuous improvement' would not be an appropriate description, since the FMEA is not constantly improved nor is the FMEA procedure a 'living' one (Bloom, 2006).

Postulate 6: *FMEA relies predominantly on expert judgment. The use of historic failure data or other measured data is generally not possible for conducting an FMEA.*
We observed that most companies find it very difficult or even disregard the option of conducting quantitative analysis, because of difficulties in acquiring sufficient reliable data. However, we did find some evidence of successful use of failure data and other measured data. First some comments on reasons why measured data should be disregarded:

> "Using data is very nice in theory, but very difficult in practice. How do we define a 'failure'? Should we include preventive maintenance? Do we treat all failures (electrical, mechanical) as equal? In addition, there is noise in the data, the data may not be registered properly. Maintenance operators are not IT-people." (Focal point maintenance and maintenance engineer *D*)

Particularly one company that indicated to have a lot of problems and to be 'fire-fighting', also claimed that data analysis was not appropriate:

"Perhaps it can be used for the final 20%, but first we have to get our regular processes in order. We have an older installation so we get more failures. We have to cut costs and reduce PM activities and we therefore have to make choices. People are critical, data are not."
This all appeared to be in line with the current postulate. However, not all companies shared this experience and opinion. Some companies did want to use more measured data, or see opportunities and two companies already do.

> "You need people and data, preferably both. I would like to use historic data, but at (*A)* there are no historic failure data available. Nor do we have the possibility to retrace historic corrective work orders. Sometimes I can use my own experience or work from memory, but that is more to trigger answers or thoughts." (Reliability engineer *A*)

> "We just invested in the integration of our SAP system with one central FMEA database. The two-way communication will enable improvement of our FMEA. Our procedures also changed, we now have to update the FMEA before we change the maintenance plan. This connects the why and how of our maintenance, in the past the why was never asked.

> The FMEA analysis is now transparent and accessible directly from the SAP system. Mechanics or operators can see where their reports are used for, this encourages accurate input. We are implementing this for two of our new plants, for our old plants we will determine focus areas."
> (Team leader maintenance *C*)

The case study showed that data needed for quantitative analyses is not always collected or the quality of data is assessed to be insufficient, e.g. data is not representative or valid. The absence of a 'clear business case' makes it difficult for the interviewees to invest time and money in improving this situation. However, *(B)* has founded a dedicated center for data management and analysis. The types of data being analyzed are process data (flow, temperature, pressure, among others) and failure data. A number of monitoring and management applications were developed, whereby the operational activities are constantly monitored and improved if opportune. Some of these applications use condition-based maintenance. In other applications, failure patterns are investigated. In addition, cross-disciplinary co-operation between engineers and maintenance experts is facilitated. In the case of (*B)*, the business case justified this investment. Ensuring the quality of reported failure data and the integration of data are challenges being managed.
A summary of the postulate discussed in Part III is given in Table 2.5.

Company	A	B	C	D	E	F
Extent to which a single FMEA administration system is being used	single system (just started with FMEA)	multiple systems	single system	multiple systems	single system	multiple systems
Extent to which the FMEA database(s) make it possible to track the reasons behind maintenance decisions	n.a.	not possible to track decision making (attempts failed), rationale not available anymore	not possible to track decision making, attempts failed, for new equipment it should be possible (not tested)	not evaluated, old FMEAs not being used	some insight in reasons behind maintenance decisions (not according to FMEA guidelines)	not evaluated, old FMEAs not being used
Extent to which FMEA is perceived as a continuous process	FMEA is a one-time exercise	FMEA is a one- time exercise, tried to reuse FMEA, instead a new FMEA has been executed. Significant current effort to introduce continuous use of data to update procedures	FMEA is a one- time exercise in the past, for new assets it is intended to re-use FMEA	FMEA is a one- time exercise	PM program is reviewed after every large overhaul	FMEA is primarily seen as a one-time exercise
Extent to which raw quantitative (e.g. failure or process) data is available and used for FMEA analysis	no usable quantitative data available, no analysis or usage	process and failure data available in data warehouse, usage of failure and process data, for Condition-based maintenance	process data and failure data in separate systems available, no analysis or usage	process data and failure data in separate systems available, no analysis or usage	some failure data available, no analysis or usage	process data and failure data in separate systems available, no analysis or usage

Table 2.5: Summary of the postulates of Part III

2.5 Summary, discussion and implications

The large body of knowledge found in the literature on Failure Mode and Effects Analysis indicates that it is an important topic in maintenance management. Other researchers have described that the method is widely used in industry, and we have witnessed six of such cases at large companies in the process industry.

Postulate	Statement	Results
1	Failure Mode and Effects Analysis is applied on a limited selection of assets/parts	Supported
2	Failure modes and effects are identified and analyzed with sufficient accuracy	Limited support
3	Failure Mode and Effects Analysis is applied according to a clearly defined paper or software procedure	Limited support
4	Following the FMEA method ensures consistency in maintenance decision making, e.g. the design of maintenance routines and maintenance planning	Not supported
5	FMEA enables continuous improvement	Limited support
6	FMEA relies predominantly on expert judgment. The use of historic failure data or other measured data is generally not possible for conducting an FMEA	Largely supported (2 companies do use data)

Table 2.6: Summary of results

The results of the multiple case study are summarized in Table 2.6.

Contrary to the original proposals on RCM/FMEA (e.g. Moubray, 1992), but in line with recent literature (Dow and Endersby, 2004, Gabbar *et al.*, 2003), the case companies followed a pragmatic approach in which the most critical assets are identified and analyzed. We have not witnessed any direct evidence that this particular approach has led to problems which could have been prevented by accepting a larger scope.

FMEA is regarded as a one-off exercise by four out of the six companies investigated. A fundamental problem appears to be that that the FMEA procedure may solely rely upon expert judgment (postulate 6 was confirmed by four out of six companies in this study) and that the expert knowledge required for this judgment is often not available because of isolation between design and process engineers, involved in the first phases of the asset life cycle and in establishing the original FMEA, and the maintenance engineers, involved in subsequent phases.

The maintenance engineers tend to update the maintenance plan, using e.g. feedback from the maintenance operators and Root Cause Analyses, without reference to the original FMEA findings, which then become out-of-date. One case company recently invested in the integration of the asset register and the FMEA database and another in founding a dedicated data management center.

In addition, the FMEA-procedure is hindered by operational (e.g. lack of a clear procedure) and information management (e.g. inaccuracy in failure reporting by the maintenance operators, relevant information distributed across various systems) problems in practice. This problem is not necessarily caused by the nature and structure of the FMEA procedure itself, but does limit its usefulness in practice. A pro-active and influential facilitator may address or limit this problem.

This study yields a number of opportunities for further research. Firstly, the study has laid bare a fundamental problem related to the nature of the RCM/FMEA procedure as well as operational and information management problems, such as data quality problems, e.g. accuracy of (failure) registration. These problems may be a good starting point for further research and development work.

Possible improvements we propose are: (1) establish data gathering policy and processes based on criticality, (2) registration of uncertainties in FMEA analysis, (3) precise registration of failure data and failure modes and (4) education on the use of quantitative analysis."

The design and use of a criticality based approach for data collection, analogues to the broadly used criticality based maintenance approach (RCM), may help to reduce efforts and improve return on investment by focusing data collection on (asset) information of asset parts that have the highest 'criticality'.

Secondly, this study may be extended to industry segments outside of the process industry. Thirdly, we have witnessed an effort to install a multi-disciplinary group with advanced data management practices and systems. Such initiatives, if successful, may prove to contain future solutions for current problems and may facilitate the further development of the use of the FMEA.

A number of limitations can be identified in the current study. Firstly, we have to recognize that plant and human safety are the most important goals for process industry firms and that this might affect the choices made in the use of FMEA results and the subsequent maintenance planning. For example, when there are uncertainties in the assumptions and findings of the analysis, then the company may decide to opt for more frequent or different maintenance than the FMEA-results would suggest. This would add to the problems described earlier in organizing continuous improvement. Secondly, the findings are all derived from process industry firms. Other industries will differ in terms of operations strategy, dominating technologies, organizational arrangements and availability of software and hardware thereby affecting the RCM and FMEA approaches. However even for those industries the results may be useful since they indicate that various types of difficulties appear in the planning of maintenance by using RCM and FMEA approaches. For instance, the importance of actively managing process engineering, maintenance engineering and operations knowledge for use in the FMEA procedure in the process industry may have its peer in other industries.

In summary, this study provided an empirical perspective on RCM and FMEA. We would like to encourage researchers to further develop practical ways to maintain the regulative cycle of continuous improvement envisaged by the developers of RCM/FMEA. Acquisition of data from the assets is generally not regarded as a useful activity, which in turn makes analysis, feedback and improvement very difficult. This stalemate situation needs to be resolved.

Acknowledgements
The authors wish to sincerely thank the six case study companies who have participated in this research.

Chapter 3

A Quantitative method for Failure Mode and Effects Analysis

Failure Mode and Effects Analysis (FMEA) is commonly used for designing maintenance routines by analyzing potential failures, predicting their effect and facilitating preventive action. It is used to make decisions on operational and capital expenditure. The literature has reported that despite its popularity, the FMEA method lacks repeatability and the ability to continuously improve maintenance routines. In this chapter an enhancement to the FMEA method is proposed, which enables the probability of asset failure to be expressed as a function of explanatory variables, such as age, operating conditions or process measurements. The probability of failure and an estimate of the total costs can be used to determine maintenance routines. The procedure facilitates continuous improvement as the dataset builds up. The proposed method is illustrated through two datasets on failures. The first was based on an operating company exploiting a major gas field in the Netherlands. The second was retrieved from the public record and covers degradation occurrences of nuclear power plants in the United States.

3.1 Introduction

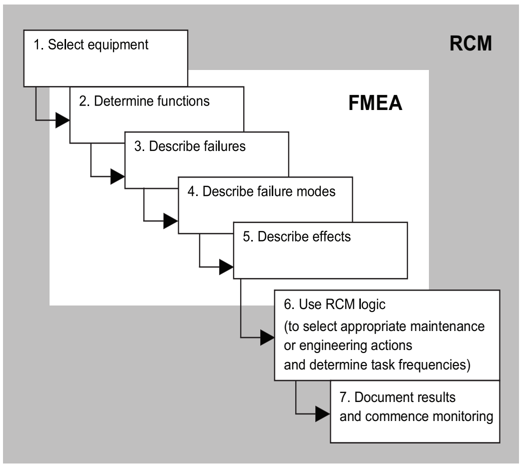

Figure 3.1: FMEA as part of the RCM process, amended from Picknell (1999)

One of the most established and widely used maintenance methods is Reliability Centered Maintenance (RCM), which originates from the defense and airline industries (Gabbar *et al.*, 2003, Garg and Deshmukh, 2006, Moubray, 1992, Riezebos *et al.*, 2009, Bloom, 2006). Failure Mode and Effects Analysis (FMEA) is a part of RCM. FMEA is described in at least four (international) standards, MIL-STD 1629A (DoD, 1980) which is used in the United States military, IEC 60812 (IEC, 1985), BS EN 60812 (BSI, 2006) and the SAE-J1739 (SAE, 2002) standard. A recent study of the current authors suggests that FMEA is indeed regularly used in practice as a basis for preventive maintenance policies (Braaksma *et al.*, 2012a). The steps within Reliability Centered Maintenance, including FMEA, are shown in Figure 1.1, which is reprinted for convenience in Figure 3.1 (Picknell, 1999). After selecting the equipment to be analyzed, the next step is Failure Modes and Effects Analysis (FMEA), which is used to identify potential failures that could have consequences affecting the functioning of a system within the limits of its application. It provides a framework for selecting appropriate maintenance or engineering actions. Failure modes are the possible ways, or modes, in which an asset can fail. Effects analysis involves predicting the effects of each failure mode (Dieter, 2000).

Failure Mode and Effects Analysis (FMEA) was developed in 1949 by the American Army to evaluate the impact of system and equipment failures on mission success and the safety of personnel and equipment (Teoh and Case, 2005). The FMEA method is a qualitative assessment of risk, predominantly relying on the judgment of experts (Moubray, 1992). For large or complex assets, it may be very difficult to replicate or improve the analysis. This is because of the complex nature of the exercise, which results in the model being static, rather than a working tool which is updated as and when required (Garg and Deshmukh, 2006, Teoh and Case, 2005).

Teoh and Case (2005) described the complexity in terms of knowledge management related to the FMEA and stated (p. 280): "when the FMEA grows, the information will be increasingly difficult to find. Eventually users will prefer to recreate their own FMEA rather than reuse existing knowledge with a risk of repeated failures". Because all experts have to be consulted again, the process can become troublesome. There is also no guarantee that the new assessment will be an improvement. From a multiple case study in the process industry, we can confirm that this complexity can indeed be found in practice.

Three factors are usually taken into account when evaluating the risk of failure: the severity; the probability of occurrence; and the likelihood of detecting the failure (Dieter, 2000, Stamatis, 2003). These are estimated through expert judgment. Previous research has proposed approaches that make the FMEA method less reliant on expert judgment and more suitable for continuous improvement (Franceschini and Galetto, 2001, Teoh and Case, 2005). Most of the existing literature has focused on quantifying the *severity* of failures and relationships between failures, sometimes including cost consequences. The literature offers several ways to value the severity of risk (or chain of risks) appropriately. Kmenta and Ishii (2000b) stated that the detection index does not accurately measure the contribution to risk and the Risk Priority Number is an inconsistent risk prioritization approach. They proposed that FMEA should be arranged around failure scenarios rather than failure modes and that risks should be evaluated in terms of probabilities and cost. Franceschini and Galetto (2001) proposed a method for calculating Risk Priority Numbers that used the ordinal features of qualitative scales to collect information from design teams. Seyed-Hosseni et al. (2006) proposed the Design Making Trial and Evaluation Laboratory (DEMATEL) method that analyzed the relationships between components of a system in respect to their failure modes and severity. Failure Mode Effect and Criticality Analysis (FMECA) is an extension of FMEA that includes severity and 'criticality' as the two risk elements. Criticality represents an indication of the sum of the probabilities of occurrence of all failure modes for a certain part or asset (DoD, 1980).

Monitoring the probability of *occurrence* has received relatively little attention in the FMEA-literature so far. If it is included in FMEA, then it is usually estimated in a qualitative way similar to the other elements. One possible reason for this could be that FMEA is often seen as a one-off exercise (Braaksma *et al.*, 2012a). A maintenance plan for addressing potential failures that fall in the category of preventive maintenance is then decided upon at the start of the plant life-cycle. As explained, monitoring and optimizing of such a plan is difficult.

We will present a proposal that includes a quantitative model for establishing the probability of failure occurrence and severity that is based on monitored dependencies (such as time and other variables) that is expressed in terms of cost. Our proposal can be used as an enhancement to step 6 of the FMEA method shown in Figure 3.1. Our scope is limited to analyzing and maintaining a group of identical assets or asset parts, although some comments are provided regarding the management of non-identical assets.

Section 2 describes the proposed methodology and presents the procedure. Section 3 demonstrates the approach in two practical applications; the first is based on an operating company exploiting a major gas field in The Netherlands. The second is using a dataset retrieved from public record that describes degradation occurrences of nuclear power plants in the United States. This is followed in Section 4 by the discussion and conclusions as well as a summary of the contribution of the chapter.

3.2 Modeling the Probability of the Failure of Assets

This section outlines the methodology of the design of the proposed enhanced FMEA method.

3.2.1 Procedure

Our model will focus on predicting the probability of occurrence of failure and the severity in terms of cost. Regression analysis is commonly used to examine the relationship between variables in probabilistic models (Hair *et al.*, 2006, Johnston and DiNardo, 1997, Verbeek, 2000). In our approach, a probabilistic model of failure is built using logistic regression. Let us assume that we have a column vector y with failure data from identical (parts of) assets that contains the value 0 if an asset i did not fail and a value of 1 if it did. Please note that we use the term 'asset' and that we could have chosen the 'part' or 'component' instead.

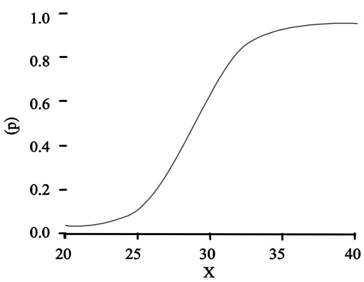

Figure 3.2: Logistic relationship dependent and independent variables

Let us also assume that we have a matrix X with characteristics of the assets that may affect the probability of failure (e.g. age, temperature, elapsed running hours) and a column vector β with values that show the effect of X on the probability of failure $p[y_i = 1]$ of asset i. β has to be estimated, y and X are assumed to be available (failure data).

With the logistic model as shown in eq. (1) one can test if asset failure can be related to the measured data (Hair *et al.*, 2006, Johnston and DiNardo, 1997). $p[y_i = 1]$ is the probability of failure of asset *i*.

$$p[y_i = 1] = \frac{\exp(X_i \beta)}{1 + \exp(X_i \beta)} \tag{1}$$

The right hand side of eq. (1) is the standard logistic distribution, which is non-linear, which allows changes of the same magnitude to have different impact depending upon the value of the explanatory variables. It also ensures that probability of predictions is in the range 0 to 1. This is illustrated in the basic example in Figure 3.2. The impact of a change in X depends not only on the size of the change, but also on the value of X. The estimation of the values in the column vector β in eq. (1) is accomplished through the use of maximum likelihood theory. The log-likelihood function for the logistic model (Verbeek, 2000) is given in eq. (2).

$$\log L(\beta) = \sum_{i=1}^{N} y_i \log F(X_i \beta) + \sum_{i=1}^{N} (1 - y_i) \log(1 - F(X_i \beta)) \tag{2}$$

Where *F(.)* is the standard logistic distribution function (Verbeek, 2000) given by eq. (3):

$$F(w) = L(w) = \frac{e^w}{1 + e^w} \tag{3}$$

After commissioning of the plant, the amount of measured data will initially be limited. The advantage of the FMEA method is that it can be used when there is not enough data for quantitative analysis (Teoh and Case, 2005). When sufficient records are available our method can be used in addition. The quantitative nature of our method makes repetition of the FMEA more easily and a 'living FMEA' as proposed by e.g. Moubray (1992), Bloom (2006) and Down et al. (2008), feasible.

Two types of data are required for our method: asset characteristics (X) and failure data (y). For the acquisition of failure data, one has to choose the time-interval. Within this interval, a sufficient number of failures should have been recorded. There is no strict rule for the number of failures to justify the logit model. However, in case one doubts if the number of failures is sufficient a complementary log-log regression can be estimated as a robustness analysis. This complementary log-log regression was especially developed to examine rare events (Cameron and Trivedi, 2005). One caveat is that the data in X should be based on measurements from before the respective failures.

The number of observations required to apply the logistic model depends on the influence of the characteristics on the probability of failure. If the engineer knows which variables are to be included in the model, power analysis can be used to estimate the number of observations that is necessary for an accurate analysis (Cohen, 1988). Long (1997) stated that analyses with less than 100 observations should be avoided and that 500 observations should be enough for most logistic models. If the number of assets is less than required, one can increase the number of observations by using multiple time intervals in which an asset fails (value 1 in y) or not (value 0 in y).

If the assets received time-based preventive maintenance and there is sufficient failure data, but little data on asset characteristics, one could still use the model by including maintenance activities in X of eq. (1) and estimating β. For example, the elapsed time between the last maintenance activity and the end of the measured time interval, or the time between maintenance and failure could be used provided that failure occurred before the end of the interval in X of eq. (1). The result reveals an estimate of the probability of failure of an asset against the elapsed time since the last maintenance activity. If there are no failure data available, one could base the probability of failure on expert opinions. Even in that case, the remainder of our procedure could be useful.

Naturally, the data used for our suggested analysis should be trustworthy, i.e. appropriately reflecting actual events. One way to achieve this is by involving operations representatives or other subject matter experts (Moubray, 1992). A potential drawback of this approach is that they can have a biased opinion and may be inclined to remove outliers, which are potentially informative. Another way is to use standard data cleansing techniques, such as trimming and 'winsorizing'. In a trimmed estimator, the extreme values are discarded; in a winsorized estimator, the extreme values are replaced by certain percentiles (the trimmed minimum and maximum) (Gnanadesikan and Kettenring, 1972).

After the model, containing values of y, X and an estimated β has been established, the next step is to evaluate the order of fit of the model. We propose the use of a Receiver Operating Characteristics (ROC) analysis for this purpose, which is a commonly used method for examining the measure of fit of probabilistic models (Fawcet, 2006).

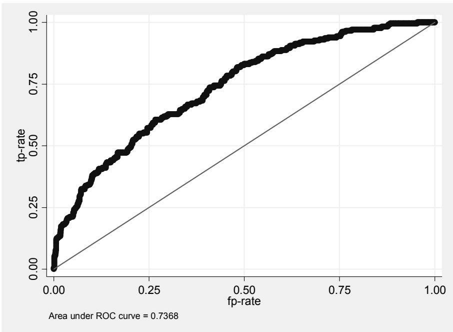

Figure 3.3: ROC-curve

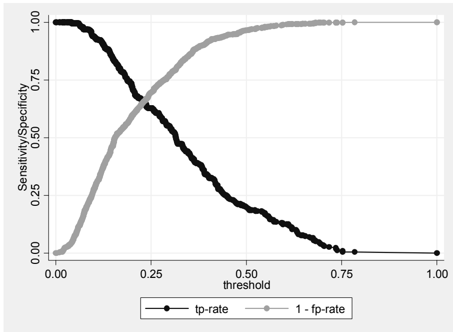

Figure 3.4: *tp-rate* and *1– fp-rate* per threshold

ROC-analysis takes into account the false positive rate (*fp-rate*) and true positive rate (*tp-rate*). A false positive in the context of failures is that the model produced an incorrect prediction of asset failure (i.e. in practice the asset did not fail). A true positive is a correct prediction of failure in a period. This failure prediction depends on the probability estimated by the model and the threshold probability set by the engineer (e.g. if the model predicts a failure probability of eighty percent and the engineer sets a threshold value of seventy percent, the engineer predicts that the asset will fail). If in reality the asset did fail, it is called a true positive. However, if the asset did not fail, it will be called a false positive. In the ideal situation, the number of true positives should be equal to the number of failures and the number of false positives should be nil and the ROC-curve, Figure 3.3 should ideally show a 90 degree line up to a tp-rate of one, after which it runs horizontally. Therefore the *fp-rate* (eq. (4), also called 1-specificity) is more informative than the number of false positives. The same goes for the *tp-rate* compared to the number of true positives, eq. (5). In eqs. (4) and (5) p_{false} and p_{true} are the number of false and true positives in a certain period; n_{tot} is the total number of negatives in that period and p_{tot} is the total number of positives.

$$fp\text{-}rate = \frac{p_{\text{false}}}{n_{\text{tot}}} \tag{4}$$

$$tp\text{-}rate = \frac{p_{\text{true}}}{p_{\text{tot}}} \tag{5}$$

The *fp*- and *tp-rates* lie both between 0 and 1. It is interesting to examine the relationship between the *fp-rate* and *tp-rate*, since the *fp-rate* should be as low as possible while the *tp-rate* should be as high as possible. The relationship between the *fp-rate* and *tp-rate* can be plotted in a so-called ROC-curve (Fawcet, 2006), an example of which is shown in Figure 3.3. An ROC-curve starts at the origin, which represents the situation in which failures were predicted not to happen in a certain period (therefore $p_{\text{false}} = 0$ and $p_{\text{true}} = 0$). The curve ends at (1,1). This point represents the situation in which each asset is predicted to fail in a given period (*tp-rate* = 1, since all the correctly predicted failures have occurred and also *fp-rate* = 1, because all the incorrectly predicted failures did not happen). In the ideal case the *tp-rate* will immediately rise to 1 (i.e. even at a low *fp-rate,* the *tp-rate* is 1). However, in the example-graph in Figure 3.2, as in most practical applications (Fawcet, 2006), the *tp-rate* gradually increases to 1 with an increasing *fp-rate*. The area under the ROC-curve is a measure of fit of the model (Fawcet, 2006). This area is related to a Mann-Witney U and Wilcoxon signed rank test and should not be confused with an R-square, i.e. an increase of say 0.1 does not mean that the model has ten percent better explaining power (Fawcet, 2006). The ROC has the advantage over R-squared, since more information can be deducted from it. By looking at the ROC it can be seen in which part the model performs well and for which part the performance is not as good. The ROC-curve can be applied to any probabilistic model and shows the benefit of using the model instead of randomly assigning failure to a certain asset (which is represented by the 45 degree line in Figure 3.3)(Fawcet, 2006).

The next step in the procedure is to determine appropriate threshold values for failure. The definition of a threshold value is given in eq. (6):

$$fail_i = \begin{cases} 1 & \text{if} \quad \hat{p}_i \geq threshold \\ 0 & \text{if} \quad \hat{p}_i < threshold \end{cases} \tag{6}$$

$fail_i$ is a Boolean variable with the expectation of failure of asset *i* and $\hat{p}_i$ is the predicted probability of failure of asset *i*. Although an ROC-curve shows the relationship between the *fp-rate* and the *tp-rate*, it does not generally convey any information for determining appropriate threshold values.

To help determine a threshold, one can plot the *fp-rate* and *tp-rate* separately[7], as demonstrated in Figure 3.4, which shows the trade-off of true positives and false positives, denoted as the sensitivity (*tp-rate*) and the specificity (1 – *fp-rate*) against all possible threshold values. If both the sensitivity and specificity are weighted equally important, 0.25 would be an appropriate threshold in the example of Figure 3.4 (the theoretical optimal threshold value would where sensitivity and specificity are both equal to 1). The maintenance cost should be taken into account when rating the importance of the sensitivity and specificity.

One could specify breakdown cost and preventive maintenance cost and calculate what the total cost of the sample would be for each threshold value. Let us assume that if $fail_i$ = 1 in eq. (6), asset *i* will undergo preventive maintenance with cost c_m (with the preventive maintenance assumed to be effective) and if $fail_i$ = 0, yet asset *i* fails, it causes a cost c_f. The total costs can then be calculated with eq. (7).

$$c_{tot} = \underbrace{c_m\left(tp\text{-}rate \times p_{tot} + fp\text{-}rate \times n_{tot}\right)}_{maintenance\ cost} + \underbrace{c_f\left(1 - tp\text{-}rate\right) \times p_{tot}}_{cost\ caused\ by\ failures} \quad (7)$$

In this equation c_{tot} denotes the total costs. Since the *tp-rate* and *fp-rate* depend on the threshold value, c_{tot} does also. Figures 3.5-3.7 show the total costs per threshold value for three specifications of c_m and c_f. Figure 3.5 and 3.7 show two extreme cases. Figure 3.5 shows a situation where preventive maintenance is never advisable, since c_{tot} decreases if the threshold value increases. This is because the failure cost is relatively low compared to the maintenance cost. Figure 3.7 shows the other extreme; the cost of failure is so high compared to the cost of maintenance that failure has to be avoided even if this means that each asset is to be maintained in each interval. Figure 3.6 shows an intermediate case, in which the point of minimum c_{tot} (0.4) can be selected as optimum. Thus each asset with a predicted probability of failure ≥ 0.4 has to be maintained.

[7] Common practice is to plot 1- fp-rate (specificity) to the threshold value but for the interpretation this does not matter (Fawcet, 2006)

3.2.1.1 Severity

The ratio of c_m/c_f can be seen as a quantitative measure of the severity. If the cost of failure is high compared to the cost of maintenance, i.e. severity is high, it is important to make sure that the asset should never fail and therefore to carry out sufficient preventive maintenance (Figure 3.7). Management can decide on which costs of failure should be included and how much this should be. The Hidden failure, Safety consequence, Environmental consequences and Operational consequences (HSEO) described in the RCM decision diagram (Moubray, 1992 p.204) can be used for this.

The model presented here adds value by improving the decision on whether to apply preventive or corrective maintenance in non-trivial cases such as shown in Figure 3.6. Moreover, if the model very accurately predicts failure it might be reasonable (from a cost perspective) not to undertake preventive maintenance on every asset, even if the severity is relatively high.

There is not a direct tradeoff between accuracy and severity. In the use of the model, the accuracy cannot be altered by the decision maker, but the (estimate of) the severity can be altered through the estimation of the various costs involved.

It is important to note that the model is maintainable. New data can first be used to predict failures. Secondly, the new data can be used to re-estimate the model and redo the analysis. The model may prevent actual failures and therefore cause new input data to diminish, and therefore the scope for further improvement in the model may diminish.

3.2.1.2 Sensitivity analysis

In contrast to the traditional FMEA method, the current regression procedure makes it possible to specify several models and compare them. It is possible to include additional asset characteristics and assess if these have a significant effect on the prediction of the probability of failure, or establish the impact of certain variables on the probability of failure. The ROC-analysis can help to examine the fit of the models. A caveat is that it may be possible to specify a model that best fits the observed data, yet it may not behave well with future data. One way to analyze the likelihood of this is by performing sensitivity analyses, by firstly determining a possible model and later to assess if the estimated parameters are sensitive to exclusion or inclusion of (new data on) asset characteristics.

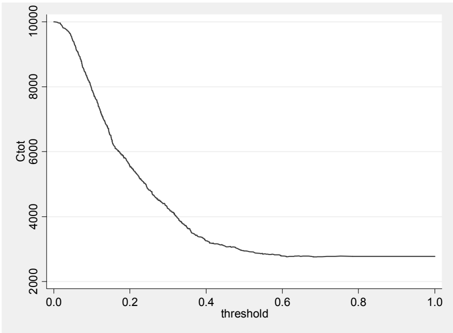

Figure 3.5: cost vs. probability per threshold (c_m/c_f = 10 / 12)

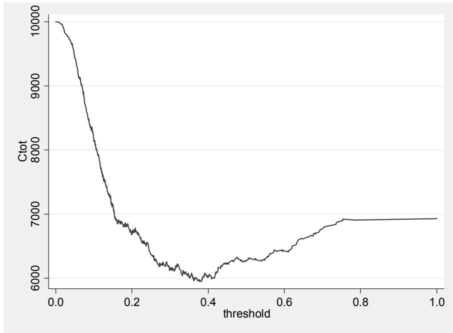

Figure 3.6: cost vs. probability per threshold (c_m/c_f = 10 / 30)

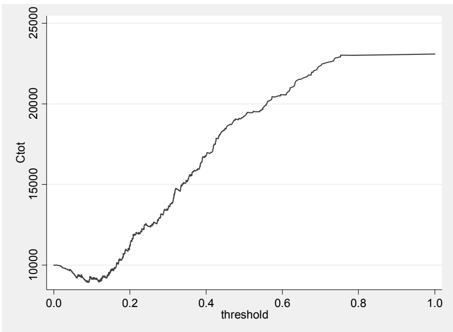

Figure 3.7: cost vs. probability per threshold (c_m/c_f = 10 / 100)

3.3 Pumps in a European gas field and US nuclear power plants

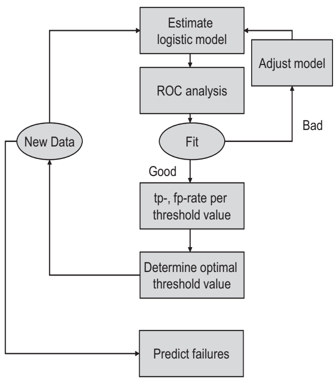

Figure 3.8: Outline of procedure

This section presents two examples of the procedure applied to datasets, which are used to illustrate the procedure which is summarized in Figure 3.8. The procedure is based on the steps described in the previous section. Some of the information which can identify the assets was altered somewhat for reasons of confidentiality.

3.3.1 Pumps in a European gas field

The Netherlands Aardolie Maatschappij (NAM) is a joint venture between Shell and ExxonMobil which is operating the Groningen gas field, which is the largest gas field in Europe. There are currently 20 gas production plants in operation that were designed using generic design standards.

The designs included redundancy for some key units (e.g. two units operating in parallel to execute one function). As an example, we will review failure data relating to one type of centrifugal injection pump, called P5A for confidentiality. Each plant is fitted with two P5A pumps that operate in parallel; therefore 40 P5A pumps are in operation, each executing the same function. Our procedure is used to analyze the occurrence of failure and the total costs of failure and maintenance and due to age (calendar time) of these pumps. Failure data was used for the period July 2006 until March 2010.

Because new equipment experiences 'childhood diseases' it is recommended that only assets running in so-called 'normal life' or 'steady-state' are analyzed (Mobley, 2004 p.3) the break-in or startup period is thus excluded. Our initial analysis confirmed that failure patterns of pumps younger than 2 years were significantly different compared to pumps older than 2 years. Therefore we focused our analysis on pumps older than 2 years. The number of observations is 1186, based on 40 pumps x 46 months (1840 observations) not including the observations of pumps below the age of two (654 observations were dropped). The number of observations we used is higher than the minimum number required for logistic modeling (Long, 1997).

3.3.1.1 Estimate logistic model and ROC analysis

We constructed a logistic model using eqs. (1-3) including the variable AGE_i, which was the age of pump i (i=1..40). Our X matrix of eq. (1) should therefore contain two columns, the first with observations on the age and the second with values 1 that represents the constant. Our y vector contains information on $FAILURES_i$, which has the value of 1 if pump i failed in the time interval July 2006 until March 2010 and a value of 0 if it did not. All pumps were maintained, after failure they got mended, no pump was replaced during the sample period. This model is represented by eq. (8). The estimated β of this model obtained via a maximum likelihood procedure are given in Table (3.1).

Table 3.1: Regression results

LOGISTIC	*B*
AGE	0.185*
	[0.072]
Constant	-4.465*
	[0.433]
Observations	1186
Standard errors in brackets. * significant at 1%.	

The results in Table (3.2) show that *AGE* does indeed have a positive significant impact on the probability of failure.

The ROC-curve belonging to the model in Table 3.1 is given in Figure 3.9, the 1- *fp*- and *tp-rate* against possible threshold values is given in Figure 3.10.

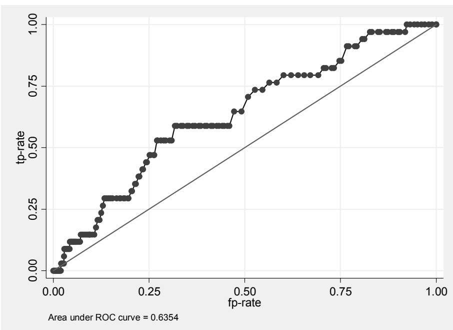

Figure 3.9: ROC-curve

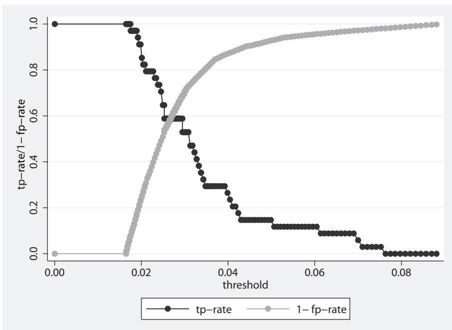

Figure 3.10: *tp-rate* and 1 – *fp-rate* per threshold

Table (3.2) shows the predictions of failures for the entire sample.

Table 3.2: Predicted probability of failures

Variable	Nr of Obs	Mean	Std. dev.	Min	Max
Predicted failure (p)	1186	.029	.013	.017	.088

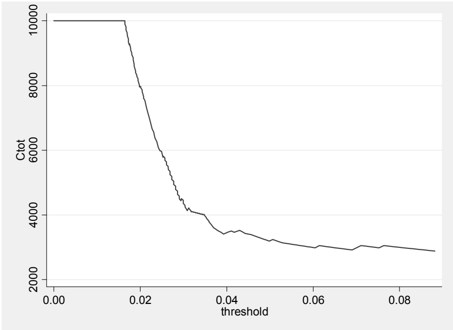

Figure 3.11: cost vs. probability per threshold (Example c_m/c_f = 10 / 100)

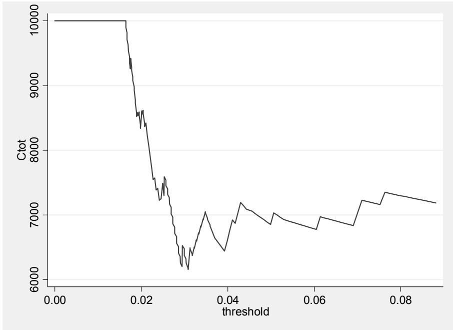

Figure 3.12: cost vs. probability per threshold[8] (Example c_m/c_f = 10 / 250)

3.3.1.2 Cost minimization by determining the optimal threshold value

If both the sensitivity and specificity are weighted equally, 0.03 would be an appropriate threshold. To rate the importance of the sensitivity and specificity, the maintenance cost should be taken into account. For the purpose of demonstrating the procedure, we have shown possible examples in Figures 3.11 and 3.12. It is possible that in the case of the investigated pumps the c_f greatly exceeds c_m as shown in Figure 3.11. However, if an optimum, i.e. a minimum c_{tot} exists, as shown in Figure 3.12, then the corresponding value of the x-axis is the optimum threshold value. This value can be used to plan preventive maintenance according to procedure described. With a cost ratio c_m/c_f = 10/100 the asset should not receive preventive maintenance whilst with a cost ratio c_m/c_f = 10/250 a threshold can be identified for the optimum. Again the expected expenditures for preventive maintenance activities and costs of failure can be determined for this optimum.

[8] The discontinuities in figure 3.12 are caused by irregularities in the ROC curve on which this threshold graph is based.

3.3.2 US nuclear power plants

The information and dataset were retrieved from the literature, in which degradation occurrences (i.e. discrete events) in US nuclear power plants were reported and important aging characteristics were identified (Braverman *et al.*, 2004, Nie *et al.*, 2008, Nie *et al.*, 2009). The number of observations is higher than the minimum number required for logistic modeling (Long, 1997) and applying the data provides basic insight in applying the steps of the procedure and possible results. This is intended as an example of the procedure, not as an assessment of the reliability and maintenance strategy of the power plants.

3.3.2.1 Estimate logistic model and ROC analysis

Braverman *et al.* (2004) demonstrated a relationship between degradation occurrences of safety-related structures and passive components and the age of the plants as explanatory variable. The dataset consists of data on 104 nuclear power plants, which are of two different types: Pressurized water reactors (PWR) and Boiling water reactors (BWR). In our example we show the PWR type, which is the most frequently used (69 plants). The timeframe chosen in this example is a period of two years (2000-2001), during which 37 out of 69 nuclear power plants produced a degradation occurrence. All reported degradation occurrences were included in our example. The selected assets that produced a degradation occurrence had a mean age of 31 years and the assets that did not do so had a mean age of 29 years (see Figure 3.2). We constructed a logistic model using eqs. (1-3). We have included the age of the plant AGE_i as a variable in our model i (i=1..69). The X matrix of eq. (3) should therefore contain two columns, the first with the observations on age and the second with values 1 that represents the constant. Our y vector contains information on $FAILURES_i$, which has the value of 1 if plant i produced a degradation occurrence in the time interval 2000-2001 and a value of 0 if it did not.

The estimated β of this model obtained via a maximum likelihood procedure are given in Table (3.3).

Table 3.3 Regression results

LOGISTIC	β
AGE	0.174*
	[0.063]
Constant	-6.177*
	[1.901]
Observations	138

Standard errors in brackets. * significant at 1%.

The results in Table (3.3) show that *AGE* does indeed have a positive significant impact on the probability of failure, the relationship would resemble Figure 3.2. The ROC-curve corresponding to the model in Table (3.3) is given in Figure 3.13). The area under the ROC-curve is 0.66 and would have been 0.5 if the model would not have added any value to a random probability of failure.

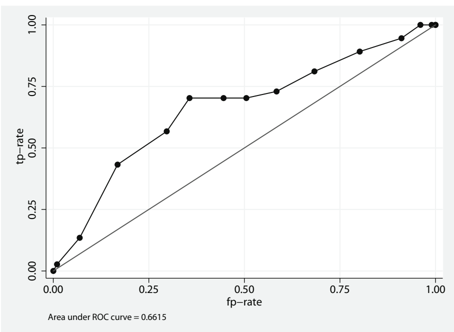

Figure 3.13: ROC-curve

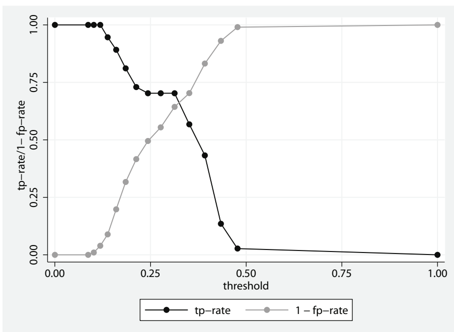

Figure 3.14: *tp-rate* and 1 – *fp-rate* per threshold

In the logistic model we find $\beta = \begin{pmatrix} 0.17 \\ -6.18 \end{pmatrix}$ so the probability of a degradation occurrence within the two-year period is

$$p\left(\left[FAILURES_{i=1..69}\right]=1\right)=\frac{\exp(-6.18+0.17\times AGE)}{1+\exp(-6.18+0.17\times AGE)} \tag{8}$$

Indeed, the probability of degradation increases with age, as shown in Table (3.4). Table (3.5) shows the predictions of degradation occurrences for the entire sample.

Table 3.4: Example of calculated probabilities of a degradation occurrence in a *yearly* period

AGE	22	24	26	28	30	32	34	35
$p([FAILURES]=1)$	0.09	0.12	0.16	0.21	0.28	0.35	0.43	0.48

Table 3.5: Predicted probability of degradation occurrences

Variable	Nr of obs	Mean	Std. dev.	Min	Max
Predicted degradation occurrences (p)	138	0.27	0.11	0.09	0.48

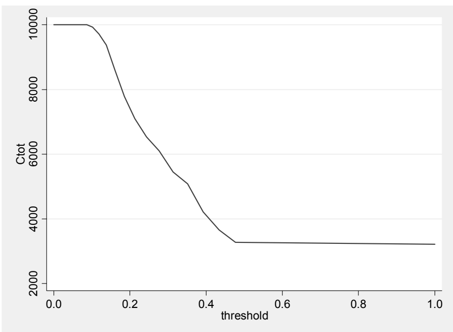

Figure 3.15: cost vs. probability per threshold (Example c_m/c_f = 10 / 12)

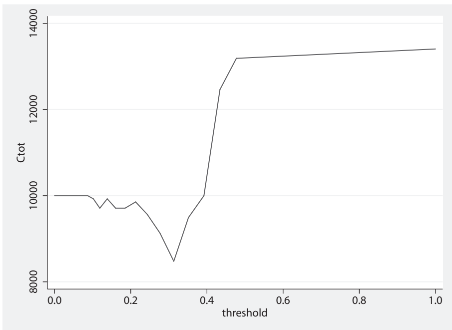

Figure 3.16: cost vs. probability per threshold (Example c_m/c_f = 10 / 50)

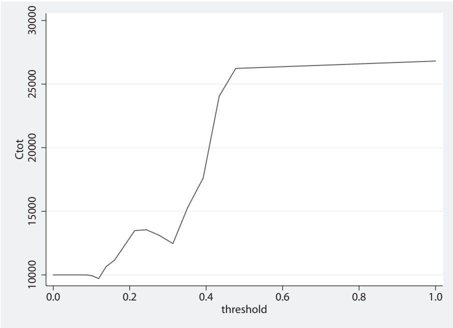

Figure 3.17: cost vs. probability per threshold (Example c_m/c_f = 10 / 100)

3.3.2.2 Cost minimization by determining the optimal threshold value

Figure 3.14 shows the sensitivity and the specificity against threshold values as in eq.(6). If both the sensitivity and specificity are weighted equally, 0.37 would be an appropriate threshold. To rate the importance of the sensitivity and specificity, the maintenance cost should be taken into account. Since Braverman et al. (2004) conveyed only very limited information on maintenance cost, we could not include exact values. For the purpose of demonstrating the procedure, we have shown possible examples in Figures 3.15, 3.16 and 3.17. It is possible that in the case of nuclear power plants, the c_f greatly exceeds c_m as shown in Figure 3.17. However, if an optimum, i.e. a minimum c_{tot} exists, as shown in Figure 3.16, then the corresponding value of the x-axis is the optimum threshold value as defined in eq. (6). This value can be used to determine which assets should receive preventive maintenance. Figure 3.15 and 3.17 illustrate extreme cases. Figure 3.16 shows a cost ratio of c_m/c_f = 10/12 and an optimum c_{tot} at approximately 0.33. This value can be used to plan preventive maintenance according to procedure described. The expected expenditures for preventive maintenance activities (c_m) and costs of degradation occurrence (c_f) can be determined for this optimum.

3.4 Discussion, summary and implications

In this chapter we have developed a procedure which enhances the traditional method of Failure Mode and Effects Analysis (FMEA). The enhancement is aimed at minimizing or compensating the weaknesses in the traditional method: reliance on expert judgment is diminished by providing a way to use historical failure data. The primary application of the model is to use the estimated probability of failure occurrence, combined with the expected cost to list the assets in order of decreasing risk.

This list can be used in the traditional FMEA analysis. Also the Receiver Operating Characteristics (ROC) analysis is demonstrated, in which the estimated probabilities are used to determine an improved corrective/ preventive maintenance policy resulting in the lowest costs.

The method is based on the use of measured data. This means that the method can be repeated in a consistent way, and can improve as the dataset builds up. In a start-up situation, with little or no measured data, the user would have to take assumptions and expert judgment as a guide to develop the maintenance routines, in a way similar to the original FMEA method.

In the development of our method we made some assumptions. Firstly, the model is of a probabilistic nature, and the results are therefore estimations based on trends rather than deterministic calculations. In case of more than one asset, data of multiple comparable assets is assumed to be available. All distributions are assumed to be normal. Secondly, it is assumed that failures do occur or have occurred, i.e. that failure data is available. If failures are avoided, for example through Condition-based maintenance (CBM) (Veldman *et al.*, 2010), then it may still be possible to use approximate failure data by assuming that failure would have happened if the condition-based maintenance actions would not have prevented it. Such combined CBM-FMEA routines are outside of the scope of this chapter. Thirdly, just as in FMECA method (DoD, 1980) it is assumed that all failures are detected, which avoids problems associated with the interpretation and measurement of the term.

For measuring it is important that the environment in which failure of parts occurs is stable for the measurement period (e.g. fixed costs resulting from failure). Fourthly, while continuous monitoring of assets is promoted in the current literature (Gorjian *et al.*, 2009) we focused on discrete occurrences. Although the concept of continuous monitoring can be included in our model by using e.g. ordered logistic models, this is left for future research. In the two real-life examples, time and cross sections are taken as equal, i.e. all physical assets are assumed to be identical. However, if data for similar but different assets is available over a certain period, it is possible to relax this assumption. Consider the situation that assets have unobservable characteristics that cause differences in the failure rate (comparable to e.g. the problem of 'Monday morning products'). There is a way to cope with such unobservable characteristics by using a panel logistic model. It is possible to estimate the logistic model with e.g. fixed effects (Allison, 2009).

We have not explored this further since it is outside of the scope of this chapter, but it may serve as suggestion for further research.
In our model we used fixed time periods; future research could explore the influence of varying time periods and varying data sets on the results. In future research we aim to further investigate the relation between explanatory variables and asset failures in practice. In addition, we discussed our model using fictitious cost-ratios. For future research it is suggested to test our model using a dataset with cost data.
Finally, we suggest to do further work on testing with small sample sizes, as in practice, companies may only have limited data. We tested our model using small subsamples and found that the stability and the accuracy of some of the subsamples are diminished and that β becomes upward biased, in line with (Nemes *et al.*, 2009). Data improvement techniques may be relevant to improve the quality of the data in this respect. Validation of the model could also be done by examining the out of sample performance of the model.

3.4.1 Managerial implications

The implications of the current development are that the enhanced FMEA method can improve or verify an existing FMEA analysis and subsequent maintenance planning actions. The analysis can provide valuable feedback on the reliability of assets and its possible consequences and potential waste or damage in terms of unnecessary maintenance or failures resulting from improper maintenance. The quantitative nature of the model makes it easier to repeat than a qualitative judgment of experts; continuous improvement is therefore easier to achieve and the quantitative nature of the results makes it easier for a board of directors to be transparent to stakeholders about asset performance and the mitigation of risks.
The main practical implication of the enhanced FMEA method is that it offers Maintenance Managers and engineers a practical tool to help solve two well-known problems currently seen in practice: firstly, serious analysis is often hindered by the reliability modeling techniques offered in the academic literature being (perceived to be) too complex to use in practice, and secondly, data gathering and data management are being neglected, thus rendering analysis attempts meaningless (Garg and Deshmukh, 2006). The proposed method aims to motivate companies to start collecting relevant and high-quality data by offering a procedure that is practically applicable and adds value through facilitating the selection of improved maintenance strategies.

Nomenclature

p	probability of failure of asset i
β	values that show the effect of X on the probability of failure of asset i
i	index assets
$fail_i$	Boolean with the expectation of failure of asset i and $\hat{p}_i$
fp-rate	false-positive rate
tp-rate	true-positive rate
p_{false}, p_{true}	the number of false and true positives in a certain period
n_{tot}	the total number of negatives in a period
p_{tot}	the total number of positives
c_{tot}	total costs
c_m	cost of preventive maintenance (assumed to be effective)
c_f	cost of failure

Appendix 3:
Application quantitative modelling results within FMEA procedure

The calculated probabilities and insights in cost of preventive and corrective maintenance policies related to actual calculated probabilities can be used as an additional input in FMEA sessions by subject matter experts. As stated, this proposal can be used as an enhancement to step 6 of the FMEA method shown in Figure 3a.1.

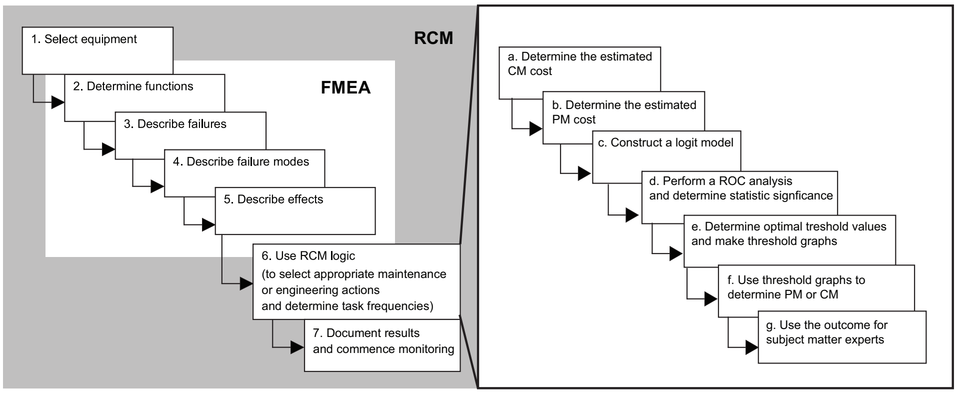

Figure 3a.1: Application quantitative modelling as part of the RCM/FMEA process, amended from Picknell (1999)

Application quantitative modelling results within FMEA procedure (step 6)

a. Determine the estimated cost of corrective maintenance for a failure mode in the selected asset in a period of time.
b. Determine the estimated cost for preventive maintenance for a failure mode in the selected asset in a period of time.
c. Construct a logit model to calculate asset failure based on the available failure (or degradation) data and possible explaining variables (e.g. age).
d. Perform a ROC analysis on the aforementioned logit model to determine tp-rates and fp-rates and determine if ROC analysis shows statistical significance.
e. Use the cost data and tp-rate and fp-rate to determine optimal threshold values and make threshold graphs.

f. Use the threshold graphs to determine the ex-ante optimum and if a preventive or corrective maintenance plan should be preferred.
g. Use the outcome as input for subject matter experts who can compare the outcome of the ex-ante optimum with other quantitative or qualitative assessments.

N.B. The determined probabilities can also be used as part of a criticality assessment (step 5, figure 3.1), the calculated probabilities can be used to make an ordinal judgment on the expected Occurrence, which is part of a regular FMEA assessment.

Chapter 4

Design of a Maintenance Feedback Analysis (MFA) method for continuous FMEA-based maintenance

Failure Mode and Effects Analysis (FMEA) is an important method to design and prioritize preventive maintenance activities. It is the basis for preventive maintenance planning in reliability-centred maintenance (RCM). From a theoretical perspective, the resulting preventive maintenance plan should be regularly reviewed based on the existing FMEA. However, preventive maintenance planning in current practice is directly updated, without use of RCM/FMEA logic, because information management is not appropriate. This brings companies to widen their safety margins and apply extra maintenance. This paper presents the design of a Maintenance Feedback Analysis method (MFA) extending the RCM/FMEA approach. The aim of MFA is to improve FMEA related information management for continuous use of RCM/FMEA logic. A design based research methodology is used. The maintenance feedback process and resultant information architecture is investigated in a case study, which leads to design principles and design requirements. The design of the MFA method is based on these design principles and requirements.

4.1 Introduction

Failure Mode and Effects Analysis (FMEA) is an important method to design and prioritize preventive maintenance activities. Within reliability-centred maintenance it is used as a basis for preventive maintenance planning (Moubray, 1992, Bloom, 2006). In current practice the FMEA plays a role when it is handed-over from design engineering to maintenance engineering. The FMEA is however not reviewed or updated anymore after its initial use (Braaksma *et al.*, 2012a, Teoh and Case, 2005, Teng and Ho, 1996). In other words, FMEA is regarded as a one-time only exercise: not as an object of development (Braaksma *et al.*, 2011). However, according to seminal authors, information feedback is essential for the success and an effective and efficient maintenance program based on a living FMEA (Bloom, 2006, Teoh and Case, 2005, Moubray, 1992).

The preventive maintenance plan might be inaccurate when used in practice. It is difficult to assess the precise impact of the inaccuracies, but it is likely that they will lead to unnecessary costs. Earlier research (Braaksma *et al.*, 2011) showed that companies have a tendency to widen their safety margins and apply extra maintenance in case of inaccuracies or uncertainties in their analyses.

Focus on the process industry

Our study focuses on the process industry, which is characterized by the need to use complex and expensive installations efficiently and safely (Fransoo and Rutten, 1994, Dennis and Meredith, 2000, Hu *et al.*, 2009). The design of the plant and equipment tends to be relatively important for safety and operational performance as compared with other industries (Gunasekaran, 1998). Structured preventive maintenance, including the use of FMEA, is therefore important for companies in the process industry (Azadeh *et al.*, 2010).

Aim and scope

The aim of this chapter is threefold: 1) explaining and exploring the RCM/FMEA related information management problems, 2) determining asset information management design principles for and 3) design of a Maintenance Feedback Analysis method (MFA) which helps to enable continuous use of RCM/FMEA procedures for maintenance planning.

Organization of the chapter

The chapter is organized as follows. In section 4.2 a literature review on FMEA-based maintenance is presented which outlines the main problems with regard to the continuous use of FMEAs for maintenance. This is followed in section 4.3 by a discussion of the research methodology applied. In section 4.4, a case study is used to explore the precise context in which feedback is collected and used for updating FMEAs. In section 4.5 the case study and literature are used for deriving design principles. In section 4.6, our Maintenance Feedback Analysis method based on the described design principles is presented. The chapter ends with a conclusion and discussion of the results in section 4.7.

4.2 Literature review

In this section FMEA, RCM methodologies and the need for a living RCM/FMEA program are discussed.

4.2.1 Failure Mode and Effects Analysis (FMEA)

FMEA is a method of reliability analysis intended to identify failures affecting the functioning of a system. It enables priorities for action to be set (BS5760, 2009). FMEA is used to identify failure modes. Failure modes are the ways, or modes, in which an asset can fail. The severity, probability of occurrence and risk of non-detection are estimated and used to rate the risk associated with each failure mode. Usual practice is to combine these elements in a 'risk priority number' (Dieter, 2000).

FMEA is widely used and described in at least four (international) standards, MIL-STD 1629A (DoD, 1980), which is used in the United States military, IEC 60812 (IEC, 1985), BS EN 60812 (BSI, 2006) and the SAE-J1739 (SAE, 2002) standard.

FMEA is an important part of Reliability Centred Maintenance, RCM, defined by Moubray (1992, p.8) as a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context. The steps of FMEA within RCM are shown in Figure 1.1, which is reprinted for convenience as Figure 4.1 (amended from Picknell 1999).

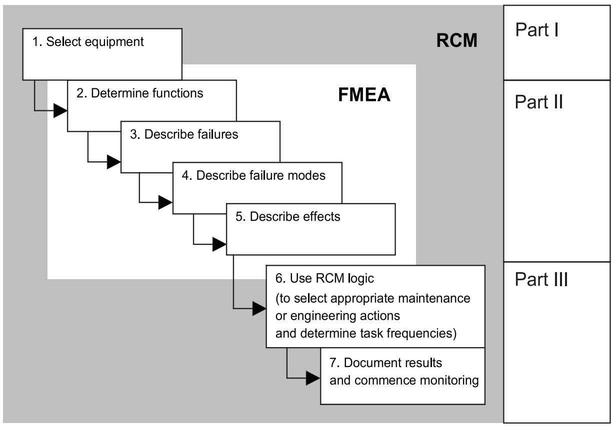

Figure 4.1. FMEA as part of the RCM process, amended from Picknell (1999)

Some authors have criticized the approach to use the FMEA in RCM because it would be complex and time consuming. Also, it would ignore existing barriers between asset management processes (Tsang, 2002).

There were also quite some critiques on the calculation of the Risk Priority Number (RPN), which is the output of an FMEA. Various altered approaches were proposed such as the FMECA (DoD, 1980), which measures criticality by translating impact into costs and ignores Detection for various reasons stated (DoD, 1980, Kmenta and Ishii, 2000a, Rhee and Ishii, 2003, Seyed-Hosseini *et al.*, 2006, Teoh and Case, 2005, Braaksma *et al.*, 2012b).

Nevertheless, the method is described as an important practice in asset management and presented as one of the key advanced maintenance procedures (Bloom, 2006, August, (2003 p.193), Moubray, 1992). The current literature predominantly covers progress in FMEA process and concept design (e.g. Sharma and Sharma, 2010, Bertolini *et al.*, 2006, Selvik and Aven, 2011), whereas the use of FMEA in a maintenance context in the process industry has been researched by Braaksma et al. (2012a) summarises the main descriptions and assumptions found in the literature on FMEA into six postulates, and compares the postulates to industrial practice.

The results suggest a fundamental problem in the FMEA procedure, namely, the reliance upon expert judgement in general and the reliance upon design engineering expertise for keeping the FMEA up-to-date in particular. To conclude: despite some criticism, literature agrees that the FMEA should be the basis for a reliability centered maintenance plan.

4.2.2 RCM/FMEA as a living program

Bloom (2006) states that the RCM/FMEA process must remain a 'living' one, never to become static. New failure modes may become evident, and additional information relative to equipment performance may present itself at any time. Oftentimes, the preventive maintenance schedule may need to be adjusted. Periodicities may need to be increased or decreased. Newly identified tasks may need to be added, while others may need to be deleted based on new or different operating conditions or plant modifications. A living program includes a feedback loop, which is important because it helps to maintain the viability of the program (Bloom, 2006). Down et al. (2008 p.63) explain that the focus should always be on continuous improvement: "After the preventive/corrective action has been completed, the (risk) priority indicator should be calculated again and revised rankings should be reviewed. If further action is considered necessary, then repeat the analysis". Stamatis (2003 p.xxvii) writes: "The push for this continual improvement makes the FMEA a dynamic document, changing as the system, design, process, product, and/or service changes". Accordingly, literature agrees that the FMEA should be a living program in RCM.

4.2.3 Information management as an enabler of a living FMEA

The information and knowledge brought together in an FMEA expert session is critical for the success of FMEA. Asset information management can therefore be viewed as enabler of feedback on FMEA and thereby as a precondition for continuous use of FMEA for maintenance improvement. Research of Braaksma *et al.* (2012a) shows however that FMEA is in practice used for one-off exercises. The FMEA-procedure is hindered in practice by operational problems (e.g. lack of a clear procedure) and information management problems (e.g. inaccuracy in failure reporting, relevant information distributed across various systems). These problems are not necessarily caused by the nature and structure of the FMEA procedure itself, but do limit its usefulness in practice.

Several authors have identified information management as a root cause for neglecting the FMEA update. They mention a number of problems with the information management of FMEA in a maintenance environment:

1. *uncertainty of future information needs*: it is unclear which data has to be registered or maintained for future asset management (Tsang *et al.*, 2006, Veldman *et al.*, 2010),
2. *maintenance knowledge is insufficiently accessible*: much of the information is embodied in a person (Moubray, 1992, Mobley and Smith, 2002, Bloom, 2006),

3. *information cannot be used without additional knowledge,* asset data is stored without sufficient context to be used effectively, (Pot, 2007, Tsang *et al.*, 2006, Teoh and Case, 2005, Braaksma *et al.*, 2012a),
4. *maintaining high quality asset data is costly and complex*: the (potential) value and quality of the often terabytes of asset information is not known, which complicates data maintenance (Garg and Deshmukh, 2006, Tsang *et al.*, 2006) (Braaksma *et al.*, 2012a), Dreverman 2005,
5. *heterogeneity of storage applications*: data is stored in several non-integrated systems, e.g. Computerized Maintenance Management Systems (CMMS), process data and RCM data which complicates analysis (Garg and Deshmukh, 2006, Smith and Hinchcliffe, 2004, Haarman and Delahay, 2005).
6. *data hand-over problems:* the breaking-point (caused by the hand-over) of asset data between maintenance and engineering (Dreverman, 2005)
7. *lack of information standards:* which complicates the exchange of asset data (Dreverman, 2005).

A literature review shows that some research has been done aimed at improving the repeatability of the FMEA analysis. Leger *et al.* (Leger *et al.*, 1999) describe a method for the automatic induction from functional analysis to FMEA and HAZOP. Teoh and Case (2005) developed the (Failure Modes and Effects Analysis Generation (FMAG) method which uses a knowledge based approach connecting the FMEA with functional diagrams. For the same purpose Dittmann (2006) proposed an ontology (OntoFMEA) for FMEA to standardize the way knowledge is described in FMEA. Braaksma *et al.* (2012b) see also chapter 3 propose a quantitative method to be used in addition to the existing method to improve the repeatability of the FMEA analysis. Veldman *et al.* (2010) describe the possible use of approximate failure data for combined CBM-FMEA routines.

From a general information system perspective Garg and Deshmukh (2006) emphasize more work needs to be done to link Computerized Maintenance Management Systems (CMMS) design and use with actual maintenance performance. “CMMS systems appear to be focused on storing equipment information and as a maintenance work-planning tool instead of use for analysis and coordination.”

In line with the aforementioned research, Kans (2008) suggests that Information technology (IT) could be an important tool for reaching efficiency and effectiveness within maintenance, provided that correct and relevant IT is applied. In this chapter, a conceptual model for identifying maintenance management IT requirements is developed.

Present research does however not address the requirements or a method enabling feedback on earlier FMEAs.

4.3 Methodology

The methodology of the chapter fits within the description of Design Science by Holmström et al. (2009), Hevner et al (2004), Van Aken (2004) and Wang and Hannafin (2005). Wang and Hannafin (2005) captures its critical characteristics: a systematic but flexible methodology aimed to improve practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories (Wang and Hannafin, p. 6).

As for the methodology of the research work reported in this chapter, the first three phases of (Holmström *et al.*, 2009) are followed: (1) Solution Incubation; Clarifying the problem, (2) Solution refinement; Identifying criteria for the intended solution, (3) Explanation I - Substantive Theory; Presentation of a proposed solution making use of identified criteria and design principles; (4): Explanation II - Formal Theory; Formal theories are aimed at broader generalizability, both in terms of theoretical abstraction and statistical generalizability.

The present case study extends on this earlier work and is aimed at further exploring the precise context of the encountered FMEA information management problems.

One of the companies was selected out of the companies investigated in Chapter 2. It was selected for its relative maturity with regard to FMEA information management as determined during the (previous) case study: the company has mature information management processes, has achieved a high level of information system integration, is actively using asset information standards and is continuously improving their (asset management) processes.

At the case company, additional interviews were conducted with relevant staff, including a maintenance manager and reliability engineers who were in some cases contracted from a specialized company. Interviewees were selected based on in-depth knowledge of the company, the assets, the way FMEAs were conducted and used for subsequent maintenance planning and the use of support systems.

After the interviews and follow-up interviews, the reports were confirmed with the interviewees. The interview data was structured and labelled. Additional data sources included earlier research, written documents and presentation material. Triangulation via multiple documents and multiple informants was used to ensure validity and reliability.

4.3.1 Clarifying the problem

For clarifying the problem and identifying criteria for the intended solution it is appropriate to use a case study (Eisenhardt, 1989, Yin, 1994, Dul and Hak, 2008, Eisenhardt and Graebner, 2007). This research work is part of a larger program; (Braaksma *et al.*, 2012a) an earlier multiple case study has been conducted on the use of FMEA in the process industry (Braaksma et al., 2012a). This study concluded that there is a fundamental problem in the FMEA procedure, namely, the reliance upon expert judgement in general and the reliance upon design engineering expertise for keeping the FMEA up-to-date in particular.

4.3.2 Identifying criteria for the intended solution

For the identification of design criteria and design principles for the proposed solution we use the information management problems identified in the case study and the literature study reported above.

For our case study we tried to get insight in the way existing FMEAs were used for review of the maintenance planning, the bottlenecks especially with relation to the information (systems) used and the context in which this bottlenecks occur.

In the context we had attention for the triggers that led to the maintenance planning review, the (quantitative) data or (qualitative) insights used for the review of the maintenance planning, how the FMEA results were recorded and managed over time and how the FMEA was used for the first preventive maintenance program.

4.3.3 Presentation of the proposed solution

Based on the clarified problem and identified criteria we present a design framework, which consist of "design guidelines" for a Maintenance Feedback Method. A design framework is described by Edelson (2002) as a "design solution" that provides a set of "design guidelines for a particular class of design challenge" (Edelson, p. 114).

4.4 Case study

In this section the case study is presented. After the case study approach (4.4.2), the FMEA process and maintenance feedback process of the studied company will be described. The company was already presented in Chapter 2 (referred to as Company B) in Table 2.3 and further.

4.4.2 Case study approach

The current FMEA process and information architecture were investigated to further explore the causes for the lack of feedback on earlier FMEA analysis. Accordingly, the research focussed on the way the earlier FMEAs were used for review of the maintenance planning. Special attention was paid to the bottlenecks in particular relation to the information (systems) used.

Therefore, the research had special attention for the (re-use of) FMEA data, the use of available (quantitative) asset data for analysis (e.g. failure data, process data), the way this data is used for the review of the maintenance planning and the way FMEA results were recorded and managed over time.

4.4.3 Description current FMEA process and maintenance feedback process

In this section we describe and compare the current FMEA process of the company with the three parts of RCM/FMEA analysis (see figure 1): (1) selection of assets, (2): FMEA procedure and (3) RCM process, reporting and feedback. We made a distinction between initial RCM/FMEA procedures and later use of FMEA for improvement of the maintenance planning. In our description of the FMEA process we focus on the information management of FMEA data.

4.4.3.1 Part 1: Identification and selection of assets

a) Initial FMEA

At the company various (critical) assets have been identified and selected for RCM/FMEA procedures through a period of 10 years. According to interviewees this has been based on criticality of the assets. There were however no records on the exact criteria or circumstances which led to the selection of assets.

b) Update maintenance planning

After some years parts of the assets have been reselected for a direct update of the maintenance planning. Careful maintenance reviews were expected to lead to more efficiency and effectiveness of the maintenance program. Another trigger was the promising use of the gathered failure data and process data in a data management system.

While the assets were reselected for a maintenance planning update they were not all reselected for a renewed FMEA analysis, this was only done when the criticality of the assets was determined as high.

4.4.3.2 Part 2: FMEA procedure: FMEA registration is limited

a) Initial FMEA

The initial FMEA approach followed by the company very much reflects the theory on RCM/FMEA procedures as described by (Moubray, 1992) and are according to the procedure described in Figure 4.1.

During the sessions the responsible maintenance engineer in the FMEA session makes notes. The resulting failure modes and RPN estimates are calculated and put into a special spreadsheet or FMEA software.

Some of the notes are personal notes of the reliability engineer for later use. The registration of uncertainties or the rationale that led to certain assessments are not described in the FMEA procedures of the company which is according to findings of (Selvik and Aven, 2011).

b) Update maintenance planning

When the maintenance planning is updated, the intention at the company is to make best use of the available information sources. Important available information sources at the company are: failure data stored in the computerized maintenance management system (CMMS), process data on a large number of components stored in a data management system, FMEA data, configuration data, engineering data, knowledge of reliability engineers and performance reports (see Table 4.2).

For the update, the performance reports and knowledge of engineers are the main information sources. Other data which is available is collected asset data, e.g. process data and failure data. The use of these data leads to different results. Some of the data is successfully used for innovative condition-based estimation of preventive maintenance. However, often the available data is not precise or representative enough for the intended data analysis. This results as a rule in neglecting (i.e. not using) the available data, but in a few cases it leads to the start-up of data collection procedures.

(CMMS) failure data	Process data	FMEA data	Configuration data
Description data types			
Three types of failure data can be distinguished: (1) Failure data generation, e.g. process data which describes off-line or fault states, (2) failures registered in a CMMS, e.g. operator failures, (3) no failure data because nothing is failing.	Process data is collected during the production process and is used for control of the process. The process data can also be used for maintenance analysis.	FMEA reports with recognized failure modes and Risk Priority estimations used for initial maintenance planning	Data which identifies and controls versioning of asset data, e.g. past preventive maintenance schedules.
Data availability for analysis			
Failure data is registered in CMMS. To use it for analysis it is uploaded to a data warehouse.	Process data is automatically collected and stored. Data from a large number of components are directly accessible for analysis in a data system	FMEA reports are stored in special FMEA databases and excel reports. The data is available in multiple formats. The originating tools which can read the data are often unavailable. Excel reports are however readable. Sometimes reliability engineers makes some personal notes	There are some documents which describe past configurations. However the CMMS used does not record maintenance history.

Table 4.2 (see also next page): Main types of data used for feedback on maintenance planning at the company and its availability for analysis

Engineering data	Knowledge of reliability engineers	Asset performance reports
Description data types		
Engineering data includes, CAD documents, P&ID schemes, test reports, etc.	Knowledge and experience of reliability engineers	Exception reports which state under performance (e.g. too high maintenance costs, low performance) of certain assets or components
Data availability for analysis		
Engineering data and output reports of FMEA are stored in a centralized Document Management System. Depending on the used tool, data is available in multiple formats.	Knowledge and experience of reliability engineers: a) tacit (personal notes and archives) b) implicit knowledge (knowledge built up as a result of experience with the assets).	Reports are based on cost data generated by the SAP system. Reports are distributed by electronic systems (e-mail) to a number of reliability and maintenance engineers.

Table 4.2: (continued)

4.4.3.3 Part 3: RCM process, reporting and feedback: no closed feedback loop

At the time the FMEA is done and the maintenance planning is determined, a future improvement of the analysis and planning is not considered (in the FMEA report).

The Risk Priority Number (RPN) outcomes of the FMEA are registered in the centrally used CMMS, underlying documents made in spreadsheets and FMEA software are stored in a centralized Document Management System.

Update of maintenance planning without FMEA logic
Based on performance exception reports of assets (e.g. high maintenance costs no failures, too many failures) the maintenance planning is directly changed/updated without use of the earlier FMEA results (see Figure 4.2). By doing so the FMEA logic is not used for the maintenance planning anymore. It is therefore difficult to appraise past decisions or to have sufficient insight in the impacts of changes to the maintenance planning.

The consequence of this might be undesirable as the criticality of assets is not necessarily included in the analysis anymore. The company indicated that this problem is prevented since the FMEA of critical assets/components is to be repeated.

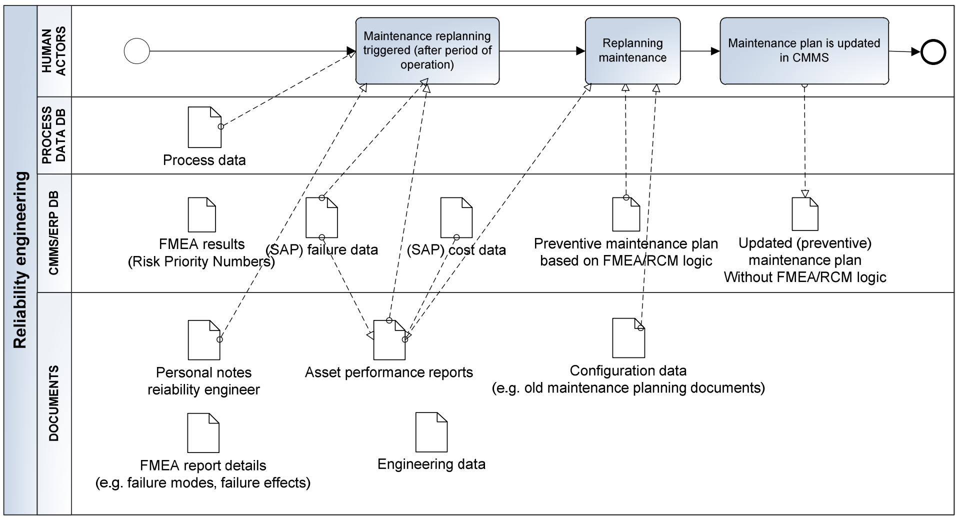

Figure 4.2: Maintenance updated without feedback on initial FMEA results (*The company*)

4.4.4 Analysis of information feedback problems

For a closer analysis of the case study there is looked at the information inputs and outputs of the complete RCM/FMEA process. The identified problems are linked to the five main information management problems mentioned in section (4.2.3); 1) Uncertainty of future Maintenance information needs, (2) Maintenance knowledge is insufficiently accessible, (3) Information cannot be used without additional knowledge, (4) Maintaining high quality information: costly and complex and (5) Heterogeneity of storage. Our case study research revealed an additional problem: (6) Information process disconnects.

4.4.4.1 Uncertainty of future Maintenance information needs

At the time the FMEA is done and the maintenance planning is determined, a future improvement of the analysis and planning is neither explicitly considered in the FMEA process nor in the FMEA reports. The responsible maintenance engineer often makes some (personal) notes for later use. The contents and quality of these notes is however not guaranteed and if a maintenance engineer leaves or gets appointed at another place often this information is lost.

4.4.4.2 Maintenance knowledge is insufficiently accessible

Despite several attempts and investments in a document management system to centrally store the FMEA reports, the company did not succeed in a useful reuse of earlier FMEAs. One of the first difficulties was accessing the digital FMEA documents.[9] However, even if the documents could be retrieved, the rationale behind the decision-making is not available in the documents.

4.4.4.3 Information cannot be used without additional knowledge

At *the company* notes are often stored in a central Document Management System, according to interviewees these notes are not interpretable by other reliability or maintenance engineers without extra knowledge on the specific asset (see figure 4.2). Asking experts who were involved earlier did also not always solve the problem as they often could only partially recall the exact circumstances in which they did the FMEAs.

4.4.4.4 Maintaining high quality information: costly and complex

Another complicating factor for the case study company is the management of large datasets with (e.g. failure and process) information on thousands of components. It is a major effort to accurately register and maintain all asset information, at the case study company multiple terabytes of asset data are available and being maintained.

When asset data (see table 4.2) are used for analysis it is needed to review the data to make sure that the data is usable. Examples of such use are filtering techniques and data acquisition techniques, e.g. running queries to integrate data from different information sources in order to find patterns of failures. There is however no guarantee that the data will be usable as the data has not been entered and maintained with future data analysis needs in mind.

---

[9] Documents containing FMEAs were stored in several different proprietary formats on the Document Management System and the software needed to read the proprietary formats was not licensed to the asset owner but to the Maintenance contractors who performed the FMEA sessions.

In our research we focused some questions on the use of asset failure data. Interviewees responded that there are substantial difficulties with using these data. Causes of the inaccuracy of failure data are according to interviewees: (a) failures are not appointed to the right functional location, (b) failure modes are not determined or not correctly assessed, (c) preventive maintenance actions are incorrectly registered as 'failure' in the CMMS. For a meaningful assets analysis it is very important that the failures are connected to the right functional location and failure mode.

Causes inaccuracy of asset failure data

The first reason for the inaccuracy of asset failure data is according to the interviewees that the registration for future maintenance analysis is not (perceived as) a core activity by the maintenance operators. Maintenance operators are more focused on registration for daily operations and execution of maintenance processes, in which inputs don't need to be as specific as for failure analysis.

A second reason is that the maintenance operators get limited feedback on the actual use of the failure details they have registered. A third reason lies in the extra effort and knowledge it takes to improve the registration. Often a failure cause is not precisely known, it takes a lot of additional to determine the cause of asset failures.

The case company did much to improve accuracy of registration, the maintenance operators were trained and were informed about the importance of good data registration. As a result the data quality did improve but there is still room for further improvement.

At the company not all root causes and failures are sufficiently important such that they need to be traced. Non-critical parts do not require the same tracking/tracing attention as parts that are determined to be critical for operations or safety.

4.4.4.5 Heterogeneity of storage

Asset data needed for feedback (e.g. failure information, process information, supplier data and FMEA reports) is in principle available but these data are stored in different systems which need to be integrated before an analysis can be made.
The quantity of data available (e.g. process data) stimulated the case study company to do supply-driven information analyses, i.e. the easy retrieval of data makes data analysis tempting. For a large number of functional locations process data is automatically collected and stored in a data warehouse.

Despite the large volume of process and failure data available, there is however no guarantee that the right data of sufficient quality is available. Interviewees could provide us with many examples in which data analysis was only partially successful because of data that was lacking or not sufficiently accurate.

4.4.4.6 Information process disconnects

A closer investigation at the case study showed that from a process perspective the problems are caused by several information process disconnects. Process disconnects are primarily the results of inadequate information management, e.g. loss of information and knowledge during time.

The identified disconnects are: (1) between the RCM/FMEA sessions and RCM/FMEA report, (2) between the RCM/FMEA analysis report and quantitative/ qualitative data analysis design and (3) between designed data analysis and actual data collection (see figure 4.3).

1) First process disconnect

A first (information) process disconnect exists between the knowledge and information discussed in the FMEA sessions and the final FMEA report that is written. In the FMEA reports of the company the full rationale behind the criticality assessments are not described. Only the RPN (Risk Priority Numbers) are put in the CMMS and some personal notes are kept by the reliability engineer, the full rationale behind the criticality assessments are not described. This kind of reports may be expected because the description of the rationale behind the criticality assessments is not part of the FMEA method. The absence of the rationale in the FMEA reports makes it difficult to appraise the quality of the FMEA and makes it difficult to analyze how the FMEA can be improved.

According to interviewees, the reliability engineer responsible for the FMEA makes some personal notes during the FMEA sessions. At *the company* these notes are not standardized in any way, at the moment the engineer leaves the organization this knowledge is often lost or hard to interpret. This is in line with earlier research that shows that FMEAs are not been prepared with the idea of re-use in mind, and are viewed as a one-time only exercise (Braaksma *et al.*, 2012a, Teoh and Case, 2005).

2) Second process disconnect

The second information process disconnect exists between the original FMEA report and the design of later data analysis studies. At the time the FMEA reports were written the case study company paid no attention to later quantitative and qualitative feedback analysis as it was not in the scope of their activities. Accordingly, there is no accurate usable list or data structure of failures mechanisms which is made available after the FMEA analysis.

An interviewee responded that a simple data structure of some failure modes (which is a higher aggregative level than failure mechanism) is available in the CMMS. In practice the maintenance engineer often enters the category: failure mode unknown. A more advanced analysis is often only performed for failures of high consequence, high repair/down time cost, or failures occurring significantly more frequent than what is considered “normal” for the piece of equipment or unit class, .i.e. worst actors.

With this approach it can however take some time before the equipment is recognized as a worst actor and it prohibits later failures to be properly related to failure modes / failure mechanisms distinguished in the FMEA. Consequently, it is not clear at later stage whether actual failures correspond to those foreseen in the FMEA or not. For example; an air filter causes problems. This can be caused by problems with the quality of the filtering system but can also be caused by changed operating conditions.

3) Third process disconnect

A third information process disconnect exists between analysis to be conducted in the future and the current collection of data (for the future analysis). Because there has been no planning for future data analysis, data is collected but not explicitly for the purpose of updating the FMEA. Analysis is primarily relying on: (1) what happens to be available in the databases of the CMMS and (2) what can be retrieved from the databases built from process data outputs. At the case study company a large amount of data was available. As mentioned, this data is not always accurate enough for analysis.

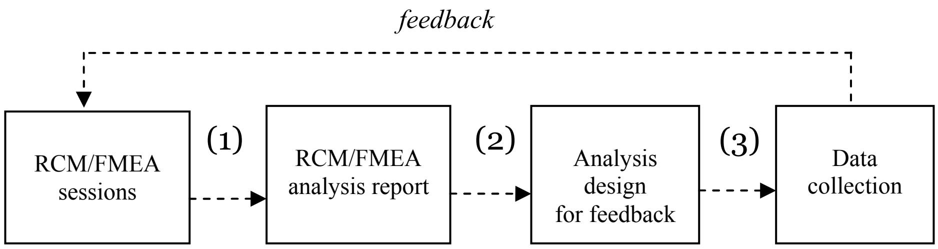

Figure 4.3: Process disconnects between RCM/FMEA and feedback

4.5 Design principles for continuous FMEA-based improvement

Based on the information management problems identified in literature and the extensive exploration of these five main problems in the aforementioned case study we propose five design principles. The design principles are aimed at solving the five main problems.

4.5.1 Describing rationale behind FMEA decision-making

Without correctly describing the supporting arguments used to determine the criticality of assets it is not possible to correctly review the FMEA. The rationale behind FMEA assessments: key assumptions and uncertainties of the assessments should be documented.

Selvik and Aven (2011) describe how uncertainties can be documented. The description of the rationale helps to recall the circumstances in which decisions have been made and lowers the amount of additional expert knowledge on the assets to interpret and improve a maintenance schedule.

The better availability of maintenance knowledge makes feedback on the used inputs in the decision making process possible and helps to determine if additional information gathering is possibly and worthwhile and helps to reduce uncertainty of future information needs. Which on it its turn helps to focus data collection efforts.

The rationale behind failure modes, failure mechanisms, estimated impacts of failures, etc. should not only be registered with regards to the outcomes of the FMEA process (i.e. RPN calculation) but should be on all steps of the FMEA process (see figure 4.1).

4.5.2 Pro-active registration of data

To bridge the mentioned process and information system disconnects we propose a (pro-active) approach. The suggested approach is pro-active because data collection is already organized before the data is actually needed or used for analysis. By following this approach the right asset data can be collected on time for the intended data analysis.

For an effective data collection one needs to identify which assets should pro-actively receive feedback and what kind of data feedback is needed on which element used in the FMEA process, e.g. with regard to the identification of failure modes, failure mechanisms, the assessed criticality, the number of expected occurrences, etc.

For example the CMMS could be set up in such a way that the engineer or operator sees a special code attached to the asset or asset part which signals how much information should be registered on the failure cause, failure mode and failure mechanism. For other non-critical assets a registration is made without special remarks on the failure cause or failure mechanisms. Other possibilities are the preparation of failure trees or failure structures, or specific instructions for diagnosis which help the engineer or operator to make a good failure registration.

With this pro-active information it is possible to plan the integration and exchange of asset information between systems.

4.5.3 Criticality based information management

A pro-active feedback approach will only be adapted in practice when it is worthwhile to do. At this moment (in theory and at the case study company) there is no differentiation in the data collection, this means that all components (thousands) are in principle treated equally. However if one concentrates on the most critical pieces of equipment which are currently analyzed at the company this number is limited to only 20 to 30 components at the time. Depending on the FMEA process and results there is a different need for feedback. For a basic quantitative MTBF analysis the data needs are different than for a more advanced analysis requiring the registration of possible explaining variables. It is suggested to start with the critical assets and look for short-term benefits which is comparable with the RCM approach (Moubray, 1992). The focus on critical assets or assets with the largest improvement potential can reduce cost of maintaining asset information while improving quality of critical asset information.

The data collection itself can also be more focused, for example on certain failure modes of selected assets. This helps to reduce the data collection effort. The exact data needs can then be communicated to maintenance operators as mentioned in the previous paragraph.

4.5.4 Demand driven analysis

By determining the needs before the data is actually collected, the data collection becomes demand-driven instead of supply driven. In a supply driven approach the analysis results are often unsure.

A demand driven approach helps to objectify data collection by a clear business case Because the demand of data is made more explicit in an early phase it enables focused communication towards maintenance operators entering and registering asset (failure) data.

The smart use data sources is very important (e.g. process and failure data) for advanced reliability analysis. The use of standards can help in integrating the various data sources (Braaksma *et al.*, 2011, Dreverman, 2005). In addition the use of business intelligence tools can help to organize data analysis. By using business intelligence tools it is possible to prepare data analysis on demand.

4.5.5 Storage of contextual data

Important for enabling a criticality based approach is the knowledge of which data is more important and should, audited more frequently or entered more frequently and helps to maintain high quality asset information data.

The importance of data should be available in the used information system, optimally an CMMS should store contextual data, in which data purposes and data collection needs are described (Pot, 2007, Tsang *et al.*, 2006).

Adding attributes to 'data critical' assets gives the possibility to differentiate in data management and focus on critical assets of which data collection is to be expected most worthwhile. Secondly it helps to communicate the importance of these assets to maintenance operators.

4.5.6 Implementation maintenance feedback planning process and supporting information system

The mentioned solution principles only help when they are implemented together and institutionalized in the maintenance processes and supporting information systems. The traditional Reliability Centred Maintenance analysis process should therefore incorporate the aforementioned design principles. A specific maintenance feedback can help to improve institutionalizing these principles.

Besides the processes an extended FMEA database should be set-up which registers: the FMEA outcomes, the rationale behind the maintenance decision making, the maintenance planning outcomes and rationale behind changes (preferably FMEA-based) in the maintenance planning.

A consistent description of data is therefore very important. One initiative aimed at the standardization of asset information is the open standard MIMOSA, which releases and maintains the so-called OSA-EAI library consisting of data models for open exchange of asset data. The MIMOSA data models can be used to set-up a asset information database for FMEA-based maintenance.

Figure 4.4 depicts the MIMOSA-EAI Core Registry Model, which is the base data model of MIMOSA-EAI.

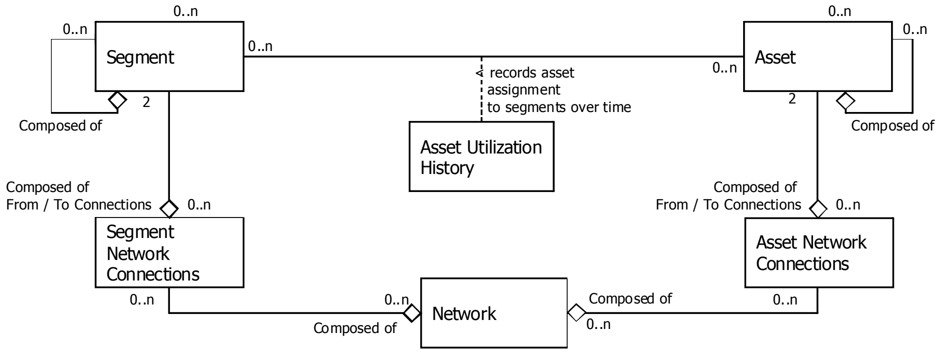

Figure 4.4: MIMOSA-EAI Core Registry Model (Bever, 2012)

4.6 Design of a maintenance feedback analysis (MFA) method

Based on the design principles identified in section 4.5: (1) Describing rationale behind FMEA decision-making, (2) Pro-active registration of data, (3) Criticality based information management, (4) Demand driven analysis, (5) Storage of contextual data and (6) Implementation maintenance feedback planning process and supporting information system.

We propose a Maintenance Feedback Analysis approach aimed improving the current asset information management and extending on the current RCM/FMEA approach. This helps to connect the RCM/FMEA outcomes with future data analysis and feedback and is intended to bridge the identified process gaps.

The MFA gives early focus on the review and improvement of the FMEA and RCM planning by establishing a data collection and analysis program before the assets clearly underperform or maintenance costs are exceeding expectations.

4.6.1 The proposed approach as extension of the RCM/FMEA method

The proposed approach is an extension of the RCM/FMEA method, step (7.) (see figure 4.5). The best moment to determine the future possibilities for feedback is at the moment RCM/FMEA sessions are being held and should be done with the same experts. Because that is a very good moment to assess the possibilities for improvement and future feedback.

Afterwards the Maintenance Feedback can be improved in iteration cycles. For some failure modes it may become worthwhile to collect data, while for others this may prove uninteresting.

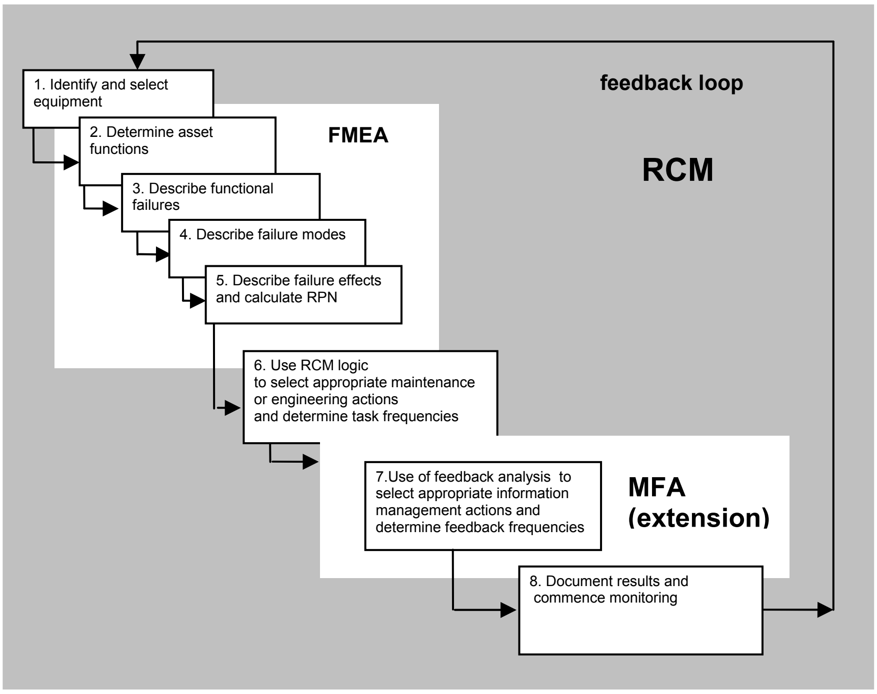

Figure 4.5: RCM/FMEA extended with MFA which enables feedback loop, amended from Picknell (1999)

4.6.2 Maintenance Feedback Analysis (MFA) steps explained

The proposed Maintenance Feedback Analysis (MFA) (see figure 4.6) consists of 4 steps which can be executed directly after the RCM/FMEA as part of an extended FMEA : (1) determine if (pro-active) feedback is worthwhile, (2) determine data analysis requirements for feedback, (3) organize data collection and (4) assure execution of the MFA outcomes. The outcomes of the MFA should be used to organize a focused data collection and data analysis which in turn can be used as feedback to improve the RCM/FMEA outcomes and can thereby improve the maintenance planning.

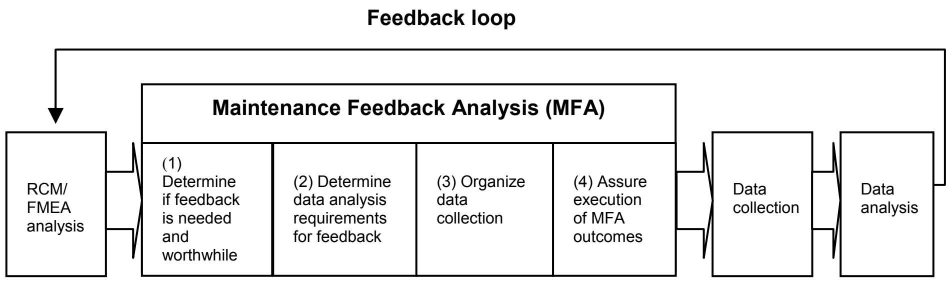

Figure 4.6: MFA steps as part of continuous improvement of maintenance

In the appendix of this chapter an example of a normal FMEA sheet based on the standard FMEA sheet which is provided by MIL-STD-1629A (DoD, 1980) and FMEA sheet including the MFA extension is provided and shows how the MFA can be integrated in a normal FMEA approach.

Step 1: Determine if Maintenance Feedback is worthwhile

In this step it is determined if there is an opportunity to improve the FMEA analysis for (the failure modes) of the most critical asset (parts). Pro-active feedback should be organized for the asset (parts) with the most significant improvement potential by determining the uncertainties and important assumptions used in the assessments of the RCM/FMEA analyses.

Main objects which should be evaluated by using MFA include failure modes and failure effects. These are both intermediary results of the FMEA and but have high impact on the outcome of the FMEA assessments.

Questions STEP 1	
1.	Describe the most important assumptions and uncertainties in the information or knowledge used in the FMEA assessment
2.	Determine if there is improvement potential to reduce the identified uncertainties, (does detailed data collection or analysis reduce the uncertainties?)
3.	Determine if it is worthwhile to reduce the identified uncertainties (yes/no, else stop)

Outcomes of step 1 are: (1) Uncertainties and causes and (2) improvement potential.

Step 2: Determine data analysis requirements for feedback

If it is worthwhile to gain more insight in the failure modes of the asset, then the next step is to decide on a data analysis strategy. Data analysis can be both qualitative or quantitative, e.g. (1) qualitative analysis, e.g. based on the experience of maintenance operators, reports of occurred failure modes, etc., or (2) quantitative analysis such as MTBF, MTTR, or MTTF or more advanced quantitative analysis techniques using explanatory variables, e.g. process analysis and condition based analysis.

Questions STEP 2	
1.	Determine what sort of data analysis should be done in the future (quantitative of qualitative)
2.	Determine the data requirements for an effective analysis
3.	Determine if it is worthwhile to do the determined data analysis (yes/no, else stop)

Outcomes of step 2 are (1) preferred data analysis and (2) data requirements.

Step 3: Organize data collection

By doing this third step the data collection needed for feedback analysis is organized and evaluated. If cost-benefit is negative then change the desired feedback analysis or data collection.

Plan organizational and technical data collection actions

Make sure possible failure modes are entered in the CMMS, e.g. the right functional locations are available. Outline the importance of data collection for the selected critical assets (register this in the CMMS) and data needed to improve performance and maintenance of this asset. Perform a cost-benefit analysis of the proposed data collection and decide on additional data-collection actions required. This third step may also involve the design of additional information systems components e.g. to plan the preparation of a data warehouse if needed and design queries for future reports.

Questions STEP 3
1. Determine to what extent the needed data is already monitored or collected 2. Determine which additional actions are needed to ensure that the desired data is collected 3. Determine if it is possible to undertake the intended actions from a cost-benefit perspective (yes/no, else stop)

Outcomes of step 3 are: (1) available data and (2) additional actions data collection.

Step 4: Assure execution of MFA outcomes

Important for the method is that the MFA is actually carried out. Besides the analysis itself, the answers to the above questions of the analysis are registered in this step together with the decisions taken. Furthermore, these decisions have to be implemented and appropriate organizational measures (such as budgeting, training, rewarding) should be taken. Periodically, the above data analysis should be scheduled as a planned maintenance action.

4.7 Conclusion and discussion of the results

We showed in our literature review and case study that because of several difficulties in asset information management the maintenance planning is directly updated without (re-) use of RCM/FMEA logic. By using the case study we further explored the context in which the FMEA is conducted and tried to be re-used. The case study identified a number of process disconnects. Process disconnects which are primarily the results of inadequate information management, e.g. loss of information and knowledge during time. We proposed design principles and design requirements enabling re-use of RCM/FMEA. By using the design principles we have proposed a Maintenance Feedback Analysis method extending the current RCM/FMEA approach.

By using MFA we first determine if feedback will be worthwhile, then the requirements for data analysis are determined in the second step, the data collection is organized in the third step and finally in step four the reporting and planning of the data analysis which assures MFA is being conducted is done. After the actual data collection and analysis the results of the data analysis can be used as feedback to the existing FMEA analysis.

The presented MFA method might be contextually-sensitive (Wang and Hannafin, p. 6) as it is designed for use in the process industry. In further research the MFA method and design principles should be as part of the used design based methodology empirically tested in different contexts. The presented method may be used as a starting point to develop better methods. The quality of (asset) information and its relationship with criticality and cost are proposed topics for further research as better insight in this relationship can improve information feedback. Finally the exchange of asset information (e.g. semantic interoperability of asset information), very important for integration of various data sources deserves more extensive research. The exchange of asset information is also discussed in chapter 5.

Appendix chapter 4:

Failure Mode and Effects Analysis without and with MFA

FAILURE MODE AND EFFECTS ANALYSIS (MIL-STD-1629A)

SYSTEM	______	DATE	______
INDENTURE LEVEL	______	SHEET	______
REFERENCE DRAWING	______	COMPILED BY	______
MISSION	______	APPROVED BY	______

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	FAILURE EFFECTS	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY CLASS	REMARKS

Figure 4a.1: FMEA without MFA

FAILURE MODE AND EFFECTS ANALYSIS WITH MFA (based on MIL-STD-1629A)

SYSTEM	______	DATE	______
INDENTURE LEVEL	______	SHEET	______
REFERENCE DRAWING	______	COMPILED BY	______
MISSION	______	APPROVED BY	______

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	FAILURE EFFECTS	FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY CLASS	REMARKS	MFA STEP (1) UNCERTAINTIES / IMPROVEMENT POTENTAL	MFA STEP (2) PREFERRED DATA ANALYSIS/ DATA REQUIREMENTS	MFA STEP (3) AVAILABLE DATA/ ADDITIONAL ACTIONS DATA COLLECTION

Figure 4a.2: FMEA with MFA

Chapter 5

A review of the use of asset information standards for collaboration in the process industry

In this fifth chapter the use of asset information standards for collaboration in the process industry is reviewed based on a survey of the literature and two case studies. The investigation shows that the process industry appears to have had only limited success in introducing such standards so far, despite significant efforts. Since information hand-over between asset life cycle phases is important, lack of information standardisation suggests that collaboration costs are higher than necessary. Reported causes can be grouped into *standard related* causes (slow development of standards, stability, complexity, cost, quality/ ontological problems), *organization related* causes (lack of direct financial incentives, organizational readiness, resistance to change) and *business environment related* causes (legal aspects, level of adoption, limited governmental enforcement and a lack of dominant actors in the process industry). It is also shown that initial local configuration of a standard may lead to successful acceptance of the standards, but may hinder later external use. The contribution of this chapter is insight into the use of asset information standards and the causes for lack of pervasiveness. This is necessary for improving the use of standards in collaboration in the process industry. The chapter concludes by suggesting future research directions.

5.1 Introduction and background

The process industry covers a wide range of activities, from continuous facilities in the petrochemical industry, to large batch manufacturing in steel production or glass manufacturing to small batch manufacturing in the food and pharmaceutical industry (Van Donk and Fransoo, 2006). Process industries are defined as adding value to materials by mixing, separating, forming, or through chemical reactions (Wallace, 1984). Processes may be either continuous or batch and generally require capital intensive installations, the design of which is relatively important and complex when compared to other industries (Dennis and Meredith, 2000, Fransoo and Rutten, 1994, Gunasekaran, 1998).

Asset taxonomies

There are several ways to differentiate between asset types and their use (Schuman, 2005, Bahill and Gissing, 1998, Chang *et al.*, 2008, Stavenuiter, 2002, ISO, 2006). The ISO 14224 standard (ISO, 2006) offers two main taxonomies for the petrochemical process industry, whereby distinctions are made between asset hierarchical class (e.g. installation, plant/unit, section, equipment unit, subunit, etcetera) and asset type (e.g. heat exchanger, compressor, piping, pump, boiler, etcetera with appropriate subunits for each hierarchical class). Many authors base their reviews on a distinction between life cycle phases (e.g. design/engineering, procurement, construction, operation and maintenance, phase-out) (Schuman, 2005, Blanchard and Fabrycky, 1998). The activities in these phases require different specialists and are often carried out by different departments or even different companies. Due to the often complex nature of the assets in the process industry and the multi-disciplinary nature of the design and optimization processes (Schuman, 2005), successful exchange of asset (design) information between disciplines and parties is in turn a prerequisite for success (Gallaher *et al.*, 2002, Shell, 1996). Asset information standards allow the interpretation of values that are shared between different business partners within and across different business processes, e.g. in exchange messages according to business protocols or in commonly used databases (Bengtsson, 2004, Burgess *et al.*, 2005, Tolman, 1999, Wilkes, 2005). Figure 5.1 shows asset life cycle phases. It highlights some typical moments for asset information hand-over.

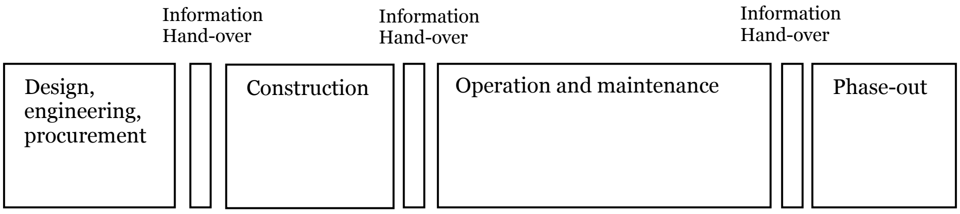

Figure 5.1: The Asset life-cycle phases amended from Blanchard and Fabrycky (Blanchard and Fabrycky, 1998)

In the current chapter, the use of asset information standards in the process industry is reviewed. As will become apparent from the review, the pervasiveness of such standards is still limited. Therefore known causes and consequences of the apparent limited use of asset information standards in the process industry are investigated and described. In addition, also the use of information standards in the aerospace and automotive industries is reviewed for purposes of comparison.

The chapter is organized as follows: Section 1 provides the introduction and Section 2 the methodology used. Sections 3 (literature) and 4 (case studies) describe the role of asset information standards in the process industry and the causes for the lack of uniform adoption and pervasiveness of the standards in the process industry. Section 5 compares the adoption of standards in the process industry with other industries. Section 6 contains the summary, conclusions and directions for further research work.

5.2 Methodology

This chapter provides insight into the use of asset information standards in the process industry and the causes for lack of pervasiveness. The chapter starts with discussing a classification of asset information standards, followed by a comprehensive description of all relevant asset information standards followed by trends in using the standards. As will become apparent from the existing literature, the standards appear to be less well used than intended. The first step towards developing a solution for this problem is to find the causes. This is done in the current chapter, through a literature survey and case studies (Eisenhardt, 1989, Meredith, 1998, Yin, 1994), and by using inductive and deductive reasoning (Holmström *et al.*, 2009, Fawcet, 2006). The result is insight, based on which solutions can be developed. However these solutions are outside of the scope of the chapter.

Case studies

The aim of the case studies is to examine the causes for success or failure in using asset information standards in the process industry, as reported in the literature. The case studies will therefore provide a first evaluation as well as practical background and detail to the findings from in the literature survey.

Both the literature survey and the case studies are still exploratory (Van Aken, 2004). Two case study companies were selected, primarily based on their maturity with regards to information management, which was established from independent reference (described below). The three main questions during the case studies were: (1) what are the reasons/ success factors for these two organizations to use (an) asset information standard(s), (2) what were the inhibiting factors and (3) how did the success factors and inhibitors found in practice correspond with the causes found in the literature?

The following criteria were set for selecting and carrying out the case studies (PDES): (1) external validity, (2) internal validity, (3) construct validity, (4) reliability. These were detailed as follows:

(1) External validity was sought by comparing cases of asset information management practice at companies with comparable practice. Two companies were eventually selected for further inspection: Stork GLT, a consortium of contractors working for is the natural gas-industry and Akzo Nobel Botlek, a process plant producing chorine products. Both organizations have internally standardized their asset information processes by making use of asset information standards.

The organizations were selected on the grounds that they have a reputation for mature information management processes. This was established by interviewing the Director of USPI-NL, the Dutch association of process industry firms. The choice was made to study these companies with significant maturity, because they are most likely to have made structured/ conscious decisions on the use of the standards. Companies without any use (some of which we have also met), simply did not show any interest and time, or were unaware of the standards. Further analysis of the lack of use would then be likely to result in speculation.

(2) Internal validity was sought by explanation-building during the case studies. The two case studies empirically investigate the context and direct reasons that impacted the use of asset information standards in the organizations. Both case studies are retrospective to the earlier engineering and construction phases. The research aim is to explore the practice of asset information standardization over the different stages of the lifecycle and its impact on the management and exchange of information inside and outside the organization. Special attention was given to the hand-over of asset information from construction to operation and maintenance.

(3) Construct validity was sought by establishing multiple sources of evidence within each of the two case study companies. This was done by using both interviews and inspection of the actual use of the asset information standards if and where applicable.

(4) Reliability or repeatability was ensured in two ways: by listing and adhering to a case study protocol and uniform storage/ reporting of the case study results. The next two sections provide a summary of these results. The case study protocol entailed the following main steps: (a) General preparation by conducting desk research of the case study companies and the asset information standards used in the industry. (b) Detailed preparation by listing interview questions, derived from the questions posed above, i.e. to investigate the causes for (lack of) use of asset information standards, with a particular comparison to the literature review. The questions were related to the organization, the design of the standards and the business environment. Sections 3.6.1, 3.6.2 and 3.6.3 are structured accordingly. (c) Determination of the persons to be interviewed and the sources/systems to be inspected. In both cases, persons were selected based on actual involvement with the use of the asset information standards and detailed knowledge of the choices made regarding the standards.

5.3 Literature survey on asset information standards in the process industry

Asset information standards in their most basic form are standardized lists of properties (e.g. the height of an object measured in millimetres). These can be defined as data models for unified description of information relating to assets or products. Most asset information standards are so-called 'neutral' standards, which can be used as an intermediary (exchange) format to make collaboration between different information systems possible. It is also possible to automate information exchange without using a neutral standard. However, for these so-called 'dedicated interfaces' a new interface has to be designed for each and every new communication (Van Renssen, 2005). Our review is limited to the use of neutral standards, since these are most suitable for extensive and dynamic collaboration (Van Renssen, 2005).

5.3.1 Classification of neutral asset information standards

Literature on specific asset information standards is not always clear about possible distinctions between the standard described and other standards. This makes it difficult to value and interpret them. This chapter creates insight by comparing the standards, which is a complicated task because of the sheer size and scope of some of the standards and also the fact that each of the standards have a different perspective on data modelling (Siltanen and Pärnänen, 2006).

An early classification to differentiate asset information standards was developed by Teeuw et al. (Teeuw *et al.*, 1996) and later amended by Van Renssen (Van Renssen, 2005), who bases his classification of asset information standards on 'semantic richness'. The semantic richness of a standard is determined by the types of relations that can be described by the standard. A lower-level standard can be used as sub-set of a higher level standard. Table 5.1 summarizes six levels. Level 1: Vocabulary, a list or collection of words or of words and phrases usually alphabetically arranged and explained or defined. Level 2: Dictionary, a reference source containing words with information about their forms, functions, and meanings. Level 3: Taxonomy, orderly classification of (parts of) assets according to their presumed hierarchical relationships, Level 4: Knowledge models, conceptual possession of aspects, Level 5: knowledge models with product structure, adds conceptual (possible) assembly relations. Level 6: a product model with any assembly relations for an individual existing product or asset.

Level	Name	Examples of asset information standards
1	Vocabulary	ISO15926-4, ISO22745, NE100/PROLIST, eCl@ss
2	Dictionary	ISO15926-4, ISO22745, NE100/PROLIST, eCl@ss
3	Taxonomy	ISO15926-4, eCl@ss
4	Knowledge models without product structure	ISO13584-501/522, NE100/PROLIST, eCl@ss (partly)
5	Knowledge models with product structure	ISO16926-7, ICAAMC compressor model
6	Individual product models	Gellish for modeling the actual data of an individual existing product or asset, e.g. K-101 the first compressor in unit 100

Table 5.1: Classification of asset information standards, after Van Renssen (Van Renssen, 2005)

Another way to distinguish standards is by viewing the functional areas of asset information covered by the standards. Fowler (Fowler, 1995) grouped the functionality of one of the most extensive asset information standards (STEP/ISO10303) into: (1) geometric description of parts, (2) configuration management, e.g. version and revision control, authorization, release status, supplier identification, (3) specifications, e.g. surface finish, material, design, process and (4) product structure.

We studied the literature on a large number of asset information standards for the purpose of our review. Most of these standards are listed in Table 5.2, which will be discussed throughout this chapter. Table 5.2 describes differences between standards. We commenced by using the taxonomy by Van Renssen (Van Renssen, 2005) to describe each of the standards discussed. As is visible in the table, some standards are all-encompassing (for example ISO15926 covering Van Renssen (Van Renssen, 2005) levels 1-6) and other standards are limited and simpler (i.e. PROLIST/NE100 and eCl@ss). Standards are often similar in structure and (technical) functionality. This may be partly explained by the fact that standards are often built on (parts) of older standards (Table 5.2). Therefore multiple standards can be used for the same purpose. This makes the taxonomy of Van Renssen useful, yet insufficient for our purpose. We have therefore added information based on type of asset (ISO, 2006), the asset hierarchical class (ISO, 2006) and the life-cycle phases/ focus areas in which the standard is used typically (Schuman, 2005, Blanchard and Fabrycky, 1998). Definitions of these three aspects were provided in Section 1.

5.3.2 Collaboration in the process industry

Since the early 90's there are, and have been, many asset information standardization initiatives in the process industry. Urban & Rangan and Betz (Urban and Rangan, 2004) describe that significant effort was put into the development of asset information standards, however compared with aerospace no really dominant standards exist. The earlier standards were developed by or under guidance of ISO, the International Organization for Standardization. ISO developed the ISO13584 PLIB (product library) standard for procurement, the STEP/ISO10303 standard which included geometric description of parts and the more recent ISO15926 standard, which includes an extensive reference data library and is specifically designed for the process industry (oil and gas). Because of the generic design, the aforementioned standards can also be used in other industries. Later asset information standards are less comprehensive and are designed for more specific purposes, e.g. PROLIST/NE100, ecl@ss, OSA-EAI and ISO14224 (see Table 5.2, column 3). Inspection of the individual standards reveals the close interdependence between (ISO) standardization initiatives; Table 5.2 highlights relationships between the standards. Older standards such as STEP/ISO10303 have been very important in that they have provided better insight into standardization requirements and thereby have pushed the emergence of newer standardization initiatives such as the development of the ISO15926 series (Van Exel, 2002).

5.3.3 Standards for different phases of the lifecycle

The role of asset information standards in different phases of the life cycle is the same, i.e. to standardize the way information is stored and exchanged. However, the information needed for the processes in different life cycle phases is different. For example in the maintenance phase a maintenance engineer is interested in reliability data for maintaining the asset whereas in the engineering phase a design engineer is interested in specification and construction data. For a process plant the amount of asset information exchanged is greater in the Engineering, Procurement & Construction (EPC) phase than in the Operation & Maintenance phase, which is the primary reason why standardization efforts have predominantly focused on the EPC phase (Lee *et al.*, 2007).

Recently the Operation & Maintenance phase has received extra attention. An example is the sponsorship by software vendor SAP of the development of OSA-EAI, a standard currently under development by Mimosa (Mimosa). Part of OSA-EAI is ISO 13374/OSA-CBM, which aims to specify a standard architecture and framework for implementing condition-based maintenance (CBM) systems, simplifying the integration of commercially available condition monitoring systems.

On a Systems engineering level (INCOSE, INCOSE, Rhodes, Bahill and Gissing, 1998), the INCOSE initiative plays an important role in achieving standardization. System engineering standards aim to automate the interfaces between enterprise and control systems. A significant development consists of the ANSI/ISA95 and IEC/ISO 62264 standards (Chang *et al.*, 2008, IEC/ISO). Together with the description of equipment hierarchies, these standards contain functional data flows and operations activity models relating to the equipment. The goal is to reduce the risk, cost and errors associated with implementing the interfaces (Chang *et al.*, 2008, IEC/ISO). Similar to OSA-EAI, the ANSI/ISA95 standard is actively sponsored by SAP.

5.3.4 Trends

Teeuw et al. (Teeuw *et al.*, 1996) describe trends for EPC environments: (1) the growing amount of asset data, as a result of increasing asset complexity, (2) the need for tighter collaboration in the engineering phase, because of the need to achieve a shorter time-to-market, (3) the need for a mechanism to effectively reuse data which is the result of a need to support product customization and product families, and (4) the tendency of organizations to focus on their core business only because assets are becoming more complex and having a shorter life cycle. Consequently the co-operation of an organization with its suppliers and customers intensifies.

A more current trend influencing the need for standards is the growing attention for safety and the environment especially in the maintenance and operations phase (Dreverman, 2005). This is often associated with the ‘license to operate’, which entails a company’s duty to manage existing and potential external liabilities, such as meeting health, safety, security and environmental (HSSE) requirements. An important aspect of the license to operate is asset integrity, which requires up-to-date available and easily accessible technical drawings, technical documentation, certificates, operating manuals and other (vendor) documentation. Asset information standards can help to maintain the required integrations and data integrity for the license to operate (Dreverman, 2005).

Table 2.2: Asset Information Standards

Name of standard *(Maintenance organization)*	**Development initiator** *(Relationships with other standards)*	**Design purpose/ industry**	**Asset information standard taxonomy**		**Asset taxonomy**		
			Typical functional areas	*Semantic richness (Meredith, 1998)*	*Type of assets (Blanchard and Fabrycky, 1998)*	*Hierarchic taxonomic level (Blanchard and Fabrycky, 1998)*	*Life cycle phases (focus areas) (Schuman and Brent 2005, Gallaher et al., 2002)*
STEP/ ISO10303 *(ISO TC184/SC4)*	Standardization organization/ scientific community *(ISO 10303-221 is based on ISO15926 - part 4)*	All	Methodology for geometric description (STEP/ISO10303 -part 2) Data modelling language for automated data exchange (EXPRESS)	1,2,3,4,5	Electrical, heat-transfer, instrumentation, static equipment, piping, valves	Usable from level 1–9 Available dictionary is on equipment level 6-9	All *(Engineering)*
ISO15926 *(ISO TC184/SC4)*	Standardization organization *(ISO15926 -part 3) is based on ISO 10303-42 and ISO 10303-104)*	All, although designed for Oil and Gas	Reference data (ISO15926 - part 4) Templates (ISO15926 - part 7)	1,2,3,4,5,6	Electrical, heat-transfer, instrumentation, static equipment, piping, valves	Usable from level 1–9 Available dictionary is on equipment level 6-9	All *(Engineering)*
PLIB/ ISO13584 *(ISO TC184/SC4)*	Standardization organization	All	Methodology for creation of data dictionaries (PLIB/ISO13584 -part 31)	1,2,3,4	Automotive, semi-conductors, sensors, electronic components, electric measuring instrumentation machineries, water sports	Libraries are mostly aimed at describing assets at a component and part level 8- 9	All *(Procurement)*
PROLIST/ NE100 *(PROLIST Int.)*	Branch *(Compliance with ISO13584 and IEC61360)*	Process industry especially for chemical plants	Asset properties	1,2,3,4	Measurement systems, process analytics, process control systems, communication systems, operations management, operational logistics systems, electrical engineering	Property lists are primarily aimed at level 8-9	All *(Engineering and procurement)*
IEC61360 *(IEC)*	Standardization organization	Process industry	Asset (hierarchical) classification Asset properties	1,2,3,4	Electrical devices	Level 6-9	Engineering and procurement
IEC61987 *(IEC)*	Standardization organization	Process industry	Lists of properties	1,2,3,4	Electrical devices, e.g. process control devices, instrumentation and auxiliary equipment	Level 6-9	Engineering and procurement
eCl@ss *(eCl@ss)*	Branch*(Compliance with ISO13584, DIN 4002, IEC61360)*	All	Asset classification and asset properties	1,2,3,4	N.a.	N.a.	All *(Procurement)*

OSA-CBM *(Mimosa)*	Not-for-profit organization (In compliance with ISO 13374-1)	All	Standardized process data for Condition based maintenance	1,2,3,4	N.a.	N.a.	All *(Operations and maintenance)*
KKS *(VGB)*	Not-for-profit organization (In compliance with DIN 6779, IEC 61346)	All, although designed for power plants	Asset (hierarchical) classification and numbering system	1,2,3,4	All types of assets used in power plants, e.g. grid and distribution systems, instrumentation, power transmission, etc.	N.a.	All *(Operations and maintenance)*
OSA-EAI *(Mimosa)*	Not-for-profit trade organization	All	Registry management, reliability information, work management, diagnostics / prognostics, condition monitoring, tests, physical tracking	1,2,3,4	All types of assets	Mostly incorporated in level 6-9	All *(Engineering, operations and maintenance)*
ISO14224 *(ISO)*	Standardization organization	All, although designed for Petroleum, petrochemical and natural gas industries	Collection and exchange of equipment data, failure data and maintenance data	1,2,3,4	Rotating, mechanical, electrical, safety and control, subsea production, drilling, well completion, well intervention, marine, utilities	All levels, although collection and exchange of data will be primarily aimed on level 6 - 9	*Operations and maintenance*
IEC/ISO62264 *(ANSI/ISA)*	Standardization Organization *(Almost similar with ANSI/ISA95)*	All	Automated interface between enterprise and control systems	1,2,3,4	Reference (process) models for varying systems	N.a.	All
ANSI/ISA95 *(ANSI/ISA)*	Standardization Organization	For global manufacturers	Automated interface between enterprise and control systems	1,2,3,4	Reference (process) models for varying systems	N.a.	All
ATA Spec 100 *(ATA)*	Branch Organization	Civil aviation	ATA numbering system	2	Aircraft systems	Aircraft numbering is comparable with plants/units (level 4)	All
iSpec2200 *(ATA)*	Branch Organization *(Based on ATA100 and ATA2100)*	Civil aviation	ATA numbering System, Maintenance Procedures and manuals	1,2,3,4,5	Civil aircraft	From aircraft (level 4) to 9	All *(Engineering, maintenance, operations)*
S1000d *(TPSMG)*	Branche organization *(Based on ATA100)*	Defence (air), but also for civil aviation and construction	International specification for technical publications but also for business requiring processes or controls	1,2,3,4,5	Defence systems – including land, sea, and air products, civil aviation products, construction industry products	From aircraft (level 4) to 9	All *(Procurement, engineering maintenance)*
ISO3511 *(ISO)*	Standardization organization	All	Symbolic representation for industrial process measurement control functions and instrumentation	1,2	Instrumentation	Level 6-9	*(Design, installation and maintenance)*
Gellish/ ISO1926-11 *(ISO)*	Science/ standardization organization *(Similarity with RDF)*	All	Taxonomy of relationships	1,2,3,4,5,6	All systems	N.a.	All

5.3.5 Use of standards in the process industry

During the 1990's there was an important increase in the development of asset information standards. This was fostered by a number of separate and international (pilot) projects concentrating on STEP/ISO10303 within the sector (Fowler, 1995). However, the initially reported momentum did not lead to sustained success (Gielingh, 2008) and the use of standards such as STEP/ISO10303 remained limited (Gielingh, 2008) to a small number of successful protocols only. From about 1996 much of the effort of the process industry was concentrated on ISO15926. The latter standard is actively supported by consortia such as USPI (NL), FIATECH (USA) and POSCeasar (Norway). However, Dreverman (Dreverman, 2005) reported that there were only few commercial implementations of ISO15926. Simpler standards (Table 5.1 levels 1-4) such as NE100 developed by PROLIST in Germany (this standard standardizes device and system properties) and eCl@ss (a standard for grouping products and services corresponding properties) appeared to have had more success in terms of actual usage.

Other more recent (pilot) project activities reported by USPI (Van Exel) are: (1) the harmonization of SAP definitions (2003-2006) by Shell, Statoil and DSM (Asset owners) by mapping these definitions to a common (precursor of) ISO15926-4 reference library. These SAP definitions are used for management of asset information in the maintenance phase mainly for procurement of parts. (2) The adoption of PROLIST/NE100 by BASF (Chemical asset owner) and Endress and Hauser (Instrumentation and DCS Equipment vendor) for procurement of electrical devices such that the engineering specification can be used throughout the plant life cycle. (3) The application of the Gellish standard for process installations in tunnels by Croon TBI Techniek (large EPC contractor) and (4) the development by ICAAMC, a global group of compressor manufacturers, of a smart dictionary based on ISO15926-4 and Gellish for the engineering specification of a compressor system such that it can be used throughout the plant life cycle.

5.3.6 Causes for lack of pervasiveness

Based on literature observations, there appear to be a number of possible causes for the lack of common adoption of asset information standards in different industries. These will be discussed below, using a grouping proposed by Wapakabulo et al. (Wapakabulo *et al.*, 2005), who made a distinction between the following success factors for standards: (1) organizational factors, (2) standard related factors and (3) (business) environment related factors.

5.3.6.1 Organizational causes

This section discusses the organizational causes for lack of pervasiveness of asset information standards.

Lack of (insight into) direct financial incentives

Perhaps one of the most important causes is the difficulty for industrial companies to judge their individual business case (costs and benefits) of adopting asset information standards. (Gallaher *et al.*, 2002, Gielingh, 2008, Teeuw *et al.*, 1996). The degree to which the benefits of standardization can be achieved depends on the degree of investment done by the collective industry in the development of the standard and by the software industry in the development of interfaces in their software. Therefore, for an individual company it may still be difficult to justify investments in standardization.

Gielingh (Gielingh, 2008) explains that the actors of which investments are required (i.e. the software vendors) are not the same as the ones benefiting from the investments (i.e. industrial end-users). In addition, for software vendors already offering integrated solutions and in possession of a substantial market share, it may be unattractive to invest in solutions that make integration with their competitors' products more attractive. If software vendors are willing to be standard-compliant, they will only invest if there is a clear market demand through a requirement by the users for inclusion of a certain standard.

Standards do not bring benefits by themselves. Benefits are indirectly related to the use of the standards. Asset information standards should be seen as an enabler of plant life cycle management. The challenge of 'measuring' costs and benefits can therefore be compared to that of other business enablers, such as ICT applications (Soh and Markus, 1995).

Organizational and industrial readiness

A natural prerequisite for an organization to use an asset information standard for the exchange of information with other organizations is that it is actually capable of using the standard (Smith, 2006). It requires understanding, preparation and discipline (Van Exel, 2002). Some authors have argued that an organization first needs to be 'ready' to use the standard for internal information exchange before it can be ready to successfully and consistently use it for external information exchange (Gielingh, 2008, Van Exel). Gielingh (Gielingh, 2008) explains that all collaborating organizations must be ready to produce and use the data, adopting the same version of the same standard and at the same level of detail. Readiness requires management support and commitment. Also resistance to change is not an uncommon challenge when it comes to implementing the use of asset information standards (Wapakabulo *et al.*, 2005).

5.3.6.2 Standard related causes

This section discusses the causes for lack of pervasiveness of asset information standards, related to the standards themselves.

(Slow) development of asset information standards

An asset information standard is a product of consensus (Dreverman, 2005, Kannengieser and Gero, 2007). Before a new asset information standard is accepted, extensive design work and discussion has taken place (Kannengieser and Gero, 2007). The reason for the (need of a) thorough process of consensus is that standards will be of higher quality, more complete, and more reflective of broad industry requirements, instead of attending to special interests (Eisenberg and Melton, 1998). Fowler (Fowler, 1995) states that 'STEP has been as much a research project as a standardization activity for much of its lifetime'. However, time-consuming development processes can lead to standards lagging behind the practices and technological developments in the industry. This can weaken the commitment of sponsors and users (Eisenberg and Melton, 1998, Tolman, 1999).

Revisioning process of asset information standards (stability of the standard)

Asset information standards are regularly revised. A case study of Wapakabulo et al. (Wapakabulo *et al.*, 2005) on the STEP/ISO10303 standard in the UK Defense industry suggests that the revision process has a negative impact on the adoption of the standard. Because newer versions lack backward compatibility with earlier versions, rework is to be done with every new version. In practice, the introduction of a different, new standard appears to have been regularly favoured over the migration of the existing standards to the latest version. This may, for example, lead to using a complex mix of old versions of some standards in combination with other, newer standards (Wapakabulo *et al.*, 2005). In aerospace, some standards provide users with tools to map older versions to newer versions (e.g. the S1000D standard) (S1000D).

Complexity of the asset information standards

The case study of Wapakabulo et al. (Wapakabulo *et al.*, 2005) on STEP/ISO10303 presents the complexity of the structure of the standard as one of the main barriers for adoption.

Smith (Smith, 2006) discusses the ISO15926 standard as an example of other asset information standards, and depicts ISO15926 as modelled 'counter intuitively from the perspective of the general users'. Mathew et al. (Mathew *et al.*, 2006) mention in their review on the use of the recent OSA-EAI/ISO13374 standard, that one of the primary issues encountered for system development is the complexity of the data model. Simplification of the data model is proposed as a result. Some software suppliers claim to reduce the complexity of a standard by the way the standard is incorporated in their software (Siemens).

Lack of accessibility to the standard (cost of the standard)

Other potential reasons for differences in popularity appears to be the lack of accessibility to the specification of the asset information standards (Smith, 2006, Wapakabulo *et al.*, 2005). This is because license fees had or have to be paid for usage of many asset information standards, as is the case with STEP/ISO10303 (Wapakabulo *et al.*, 2005) and ISO15926 (Smith, 2006), which are copyrighted by the International Organization for Standardization, from where it can be purchased. Although the fees are small it is felt as a practical obstacle. The incorporation of standards in software, e.g. S1000d in Siemens PLM software (Siemens), reduces the need for an end-user to have access to the original standard.

Quality of asset information standards

a. Ontological problems

An asset information standard is the end-result of many decisions and is therefore often a compromise. Smith (Smith, 2006) discusses some (ontological) mistakes, which occur in the development of asset information standards which may influence the user-friendliness and usability of the standards. Smith takes the ISO15926 asset information standard as an example. Smith (Smith, 2006) mentions the following problems: (1) terminological confusions, expressions such as 'instance', 'entity', 'object', 'represent', etc., are used in different ways by different communities, and (2) the employment of logical tools in a counterintuitive way.

A problem of ontological choices with some asset information standards is that they cannot be reversed easily; asset information standards such as ISO15926 are built like houses on foundations. Past choices can hinder or block future progress, for example information systems, which rely on predefined structures can have problems if data is modelled in another way than was pre-defined in the information system.

There appear to be two traditional solutions for solving this problem: to add new sections to standards or to design new (versions of) standards, e.g. instead of changing the architecture of STEP/ISO10303, a new standard ISO15926 was developed. Such solutions might also complicate things. Future research on (automatic) mapping of different asset information standards or versions of standards appears to be promising for solving this problem (Bellatreche *et al.*, 2006, Kannengieser and Gero, 2007, Li *et al.*, 2005, Silva *et al.*, 2005).

b. Poor performance of asset information standards

Gielingh (Gielingh, 2008) mentions the poor performance of current asset information standards. The exchange of data using neutral files is not without errors which is illustrated by three exchange projects in which serious loss of the original design-content (geometric data) occurred. Remarkable was that the applications involved applied the standard correctly. Gielingh (Gielingh, 2008) concludes that errors cannot fully be avoided. Anomalies in the exchange appear to differ from application to application and from translator to translator.

c. Asset information standards not really neutral models

Gielingh (Gielingh, 2008) explains that asset information standards are not really able to fulfil the collective requirements of many specific collaborations (made specific by the exact nature of the information exchange). In his view, the result is that the focus of asset information standards has shifted from one area, i.e. dedicated interfaces, to another, i.e. customizations of standards, e.g. 'conformance classes' and 'AP's' (=Application Protocols, large and comprehensive data specifications that satisfy the specific product data needs for use in specific industry segments). This would also help to explain why vendors are reluctant to develop standard-compliant commercial applications, since standard-compliancy may not guarantee that the applications are actually fit for purpose in many situations.

5.3.6.3 (Business) environment related causes

This section discusses the causes for lack of pervasiveness of asset information standards, as far as the causes are related to the business environment.

Extent to which asset information standards are already adopted (e.g. in industry)

An important enabler of adoption of asset information standards mentioned by Wapakabulo et al. (Wapakabulo *et al.*, 2005) is the extent to which asset information standards are already adopted. This phenomenon is also supported by network analysis theory (Wapakabulo *et al.*, 2005), whereby it of the utmost importance to gain momentum. After the mores in a particular industry are (more or less) set, further adoption will be easier. This may be initiated by so-called dominant actors; large companies or governmental bodies enforcing the standards. Lack of dominant actors enforcing a standard may be one cause for limited use (Dreverman, 2005).

Legal aspects

A barrier for the uptake of asset information standards mentioned by (Gielingh, 2008) are legal aspects. Legal processes usually assume the usage of paper documents. Electronic documents may be acceptable, if they are printed or made available in a widely accepted format. This is further complicated by liabilities and contractual dependencies. The application of an asset information standard requires a contractual agreement between two industrial parties who intend to exchange product data. The performance of this exchange depends on (contractual) commitments between industrial parties and their vendors. Secondly the actual exchange requires translation between source and target-applications. If anything goes wrong with the exchange and if it is not directly clear what causes the problem, it will therefore be difficult to hold one of the parties liable for problems with standards based data exchange.

5.4 Two Case studies (Stork GLT and Akzo Nobel Botlek)

This section presents the two case studies, in which the causes for success/failure in using asset information standards in the process industry as reported in the literature are examined further.

5.4.1 Case 1: Stork GLT

Stork GLT VoF is a consortium consisting of five contractors and suppliers, which are committed long-term to the engineering, renovation, maintenance and modification activities for one of Europe’s largest gas assets. The asset is operated by NAM, a joint venture between Shell and ExxonMobil. NAM is organized as an operating company of Shell. Production facilities consist of 20 installations throughout the northern part of The Netherlands (Sietinga *et al.*, 2008).

The close cooperation between NAM and the consortium Stork GLT and within the consortium has intensified the need for information exchange and standardization. Stork GLT makes use of neutral asset information standards (STEPlib; part of STEP/ISO10303) which is actively used for classification of documents, the plant breakdown structure and the unique numbering of asset parts. Although the standard is used to a considerable extent, there was more functionality available in the standard than was selected (e.g. complex product models). Through structured interviews, the causes for the decisions in the use of the standard were established. These are summarized below, structured in the same way as the results from the literature review.

5.4.1.1 Influence of the Organization

This section lists the aspects found during the case study related to the organization.

Insight into direct financial incentives

At the time that the choice was made to implement asset information standards (in the design and engineering phase) there were no clear business cases or reports of estimated benefits available. As an interviewee said 'There was a belief, a vision that the use of standards would bring benefits in the efficiency and effectiveness for the information exchange within the consortium.' This may be explained by how the consortium is organized and managed from the beginning. Within the consortium the organizations are able to propose the best solutions within the functional specification provided by NAM, instead of merely being allowed to work in a prescribed way and execute tasks within technical specifications (Sietinga *et al.*, 2008). This resulted in strong ownership for the best solution and processes, including asset information management.

The application of the data management standard (STEPlib part of STEP/ISO10303) proved useful, not so much in the communication with third parties but more in the internal communication between disciplines and applications. For example, when design data had to be imported into the SAP maintenance system, the names and data structures were already consistent, which simplified the data-import (Sietinga *et al.*, 2008).

Organizational and industrial readiness

Because Stork GLT had to start from scratch (in 1997), it was possible to implement the standards in a green-field environment. There was a common belief that standardized registration would benefit the organization, therefore there was little resistance to the use of the standards.

Later, when Shell and NAM standardized information management (through the use of a SAP-based system) there was some natural resistance of the consortium members to change to this new standard. The benefits for the internal processes of Stork GLT was expected to be limited, since the existing standards worked well. The change would however bring standardization benefits to Shell and NAM, and the communication between Stork GLT and NAM. Because the information management was already internally standardized it was not too difficult to adapt to the new standard.

5.4.1.2 Influence of the Standard design

This section lists the items found during the case study related to the design of the asset information standards used.

Complexity of asset information standards

The implementation was not seen as a complex task. Reasons given for this are the fact that the standard could be implemented in a newly founded organization (green-field), together with the pragmatic approach chosen by the organization. Making sure the standard is used consistently over a long time period despite changes of personnel and lifecycle phases is seen as a 'far more difficult task'.

Accessibility to the standard

There were no reported problems with access to the standards, which may be the result of some consulting contacts with experts within the community, which produced the STEPlib standard. Gaps or difficulties with regard to the specifications were bridged by a pragmatic implementation of the standard. This had as a consequence that some of the neutrality of the standard was lost in the implementation process. With neutrality we mean the possibility to easily exchange the internal standardized information with external communities (outside the consortium) which are also using the STEPlib standard.

Quality of asset information standards

There were no reported problems with the implementation and use of asset information standards, one of the reasons might be the fact that Stork GLT chose to only implement the most elementary parts of the STEPlib library. Another reason may be that Stork GLT makes use of a central engineering database, in which most engineering details can be accessed/progressed by all consortium employees. The use of the standard is embedded in the use of this system, which is prescribed and controlled centrally.

Quick development of asset information standards

Stork GLT was at the time of implementation, in the late 1990's, aware of the development of the STEP (ISO10303) standard. Early contacts with experts taking part in the STEP development led to the decision to develop and implement the STEPlib standard internally with a small group of key people by using a pragmatic approach. Only the parts which were really needed in the view of the organization were used. When there was discussion about the way the standard should be implemented, the organization chose for a pragmatic solution which was most simple to implement but also led to abandoning the standard sometimes. This way of working facilitated a quick development and implementation of the standard.

5.4.1.3 Influence of the Business environment

This section lists the items found during the case study related to the business environment.

Existence and influence of dominant actors

Asset operator NAM can be seen as a dominant actor influencing the use of standards in general. They did not force the adoption of specific asset information standards in the engineering phase but were very active supporters of standardization in the start-up phase. NAM as an organization was actively participating in standard development and aware of potential benefits of asset information standards.

5.4.2 Case 2: AkzoNobel Botlek (MEB)

AkzoNobel Botlek MEB (Membrane electrolysis) primarily produces chlorine, caustic soda, and hydrogen. The company is an example of an organization in the process industry that internally standardized many of its asset information management processes and slowly defined their own internal (asset information) standard. The internal standards are often based on national or international standards, for example ISO3511 for Piping and Instrumentation Diagrams (P&ID).

The activities of AkzoNobel Botlek cover all processes in the asset life-cycle from engineering to construction, operation and phase-out. This means that it is possible to implement and stimulate the use of a shared asset information standard. Examples of information carriers for which asset information standards are used are piping and instrumentation diagrams (P&ID), asset numbering (identification), and pipe classes (material norms).

5.4.2.1 Influence of the Organization

This section lists the aspects found during the case study related to the organization.

Insight into direct financial incentives

AkzoNobel Botlek did not explicitly measure the financial benefits of the use of standards. The engineering organization, driver of the use of the standards, again worked from a common belief that it would be beneficial. The recent outsourcing of maintenance activities to a maintenance contractor made the importance of stringent standardization even more clear. As one interviewee said: "Standardization was something done by the internal engineering department and was being done because this just seemed to be a task they had to do." When AkzoNobel Botlek selected the external maintenance contractor, the contract was not clear about the responsibilities for information maintenance and the use of standards. "This has led to configuration management problems, some of which have yet to be resolved".

5.4.2.2 Influence of the Standard design

A side effect of the choice of AkzoNobel Botlek for a pragmatic implementation of the asset information standards is the loss of neutrality. In fact by tailoring the asset information standard a new local standard is established. This has not been regarded as an issue by AkzoNobel Botlek yet as almost all asset information exchange within the organization is standardized to the tailored version of the standard. However, AkzoNobel Botlek has recently outsourced activities to a partner which does use a (neutral) asset information standard. This means that a translation is necessary.

The problems related to 'loss of neutrality' are explained through a simple fictitious example (not directly related to AkzoNobel Botlek):

- If one company uses a dedicated standard for denoting a percentage (e.g. ".50") and a partner company uses the exact notation as dictated by the neutral standard (e.g. "50%) then a mismatch will occur. In this case the solution is straightforward: a simple translation between the dedicated format and the neutral standard format is sufficient.
- If the partner would also have used a customized standard (e.g. with notation "0,50"), than a second choice would be necessary: either translation between customized and customized, or with translations to the neutral standard as an intermediate step (e.g. ".50" to 50% to "0,50").

- The decision and implementation will be even more complex if information would go lost in the translation (e.g. ".501" to "50,1%" to "0,50").

5.4.2.3 *Influence of the Business environment*

This section lists the items found during the case study related to the business environment.

Existence and influence of dominant actors

For a long time, the use of the standards was mainly internally. This was driven by Engineering, which in turn acted upon the demands of the Engineering function of the group AkzoNobel, of which AkzoNobel Botlek is a subsidiary. In this way, Engineering and the group-company became the dominant actors. Initially, there was limited drive for stringent use of the standards in communication with external parties. However, there have been some changes recently, which included the outsourcing of some of the maintenance activities and also the vision that, if (internal) standardization was to be maintained, also the (new) external/contracting parties are to work according to the standards. This was made explicit by agreeing that the contractors would work in the AkzoNobel Botlek engineering database.

Legal aspects

There are no reported problems with regard to legal aspects, which may be because of the sharing of interests within AkzoNobel Botlek internally so far.

5.4.3 Comparison

The two case study companies were primarily selected for their maturity in using asset information standards, which was established from independent reference. We know from the literature that asset information standards are not used pervasively in the process industry. The three main questions during the case study were: (1) what are the reasons/ success factors for these two organizations to use an asset information standard, (2) what were the inhibiting factors and (3) how did the success factors and inhibitors correspond with the causes found in the literature (Figure 5.2, Table 5.3).

(1) Success factors

In both cases, the organizations did not have a clear idea of the direct financial incentives. Rather, the implementation was initiated from a belief or a sense of duty. In both cases, there was a governing organization (the client in one case and the parent-company in the other) acting as dominant actor in encouraging and facilitating the implementation. Organizational readiness proved sufficient in both cases, which is not surprising, since the companies were selected for their maturity in information management. In both cases, the standard was at first mainly used for purposes of internal information exchange. Later, external influences enforced the need to also exchange external information in a standardized way. The initial implementation was therefore selected and configured, and in case 2 also tailored, to suit the needs of the company and the users. This helped acceptance of the standards, but also introduced a (potential) inhibiting factor.

(2) Inhibitors

After successful implementation predominantly for internal use, both case companies were forced to also facilitate external information exchange in a standardized way (albeit for different reasons). The initial success factor (i.e. locally made choices and therefore acceptance in the organization) now became an inhibitor: the use of the standard had to be broadened. This led to additional effort in both cases. This raises an interesting question: would it have been possible to configure the standards for local use and acceptance in such a way that later global use would not have cost additional effort?

(3) Comparison with the literature

Both organizations claim to benefit primarily from improved internal communication (engineering-procurement-construction-operation/maintenance) and later, or to a lesser extent, from improved external communication. This is consistent with the business needs and how they evolved over time: at first, the organization had to be streamlined internally, after which external communication and/or outsourcing could be organized.

Both organizations were pragmatic in the way (sections) of asset information standards are implemented. This appears to have aided the use and acceptance of asset information standards in both organizations. In the case of Stork GLT the green-field start and use of a central database also stimulated the use of asset information standards. For AkzoNobel Botlek it was possible to implement the standards because of the influence of the engineering organization.

In conclusion, there appears to be a paradox with regard to successful implementation of the standards. The pragmatic use of standards (which may include local configuration/ customizations) may lead to successful use and acceptance locally, but does not make it easier to have different communities connect to each other. In fact, one could say that new, local standards are created. This apparent paradox touches upon the classic discussion of centralization and decentralization (Negandhi and Reimann, 1973).
Further research could perhaps aid in the development of standards which allow such customizations whilst still preserving the pervasive potential of the standards.

5.5 Adoption of asset information standards in other industries

In order to investigate other possible causes of lack of adoption, as well as possible solutions, a comparison was sought with other industries, in which asset information standards are important (and important progress was made): the aerospace industry and the automotive industry.

5.5.1 Aerospace

The aerospace industry can be viewed as leading when it comes to asset life cycle management and adoption of asset information standards (Lee *et al.*, 2007). For example, parts of the STEP/ISO10303 standard were successfully implemented by e.g., Boeing, Lockheed Martin and NASA, who were all reported to use several STEP Application Protocols (AP) for collaboration (Smith, 2002, PDES). Integration between the processes governing the life cycle phases of aircraft was adopted in aerospace because of several reported reasons, which are primarily based on the fact that the lifespan of an average airplane is long (more than 30 years), which leads to opportunities for investments in design and optimization processes. This in itself is not different from the long lifespan and significant opportunities in designing and optimizing a process plant. However a process plant is often built as one-of-a kind whereas aircraft are made in series, which enlarges the opportunities for fruitful investments in design and optimization processes.
In addition, pressure of governmental safety regulations forced or stimulated the adoption of asset information standards (Dreverman, 2005, Lee *et al.*, 2007).

The proprietary (and in principle non-neutral) aerospace standard iSpec2200, which was developed by ATA (Air Transport Association), is also successful. iSpec2200 is based on the earlier ATA 100 spec and ATA 2100 spec standards. These contain format and content guidelines for technical manuals written by aviation manufacturers and suppliers and are used by airlines and other segments of the industry in the maintenance of their respective products (Wikipedia). iSpec2200 is a suite of data specifications and data models for the digital representation and exchange of technical data. Functional areas are: the industry-wide ATA numbering system (based on ATA 100 Spec), maintenance requirements (e.g. scheduled maintenance and maintenance planning), maintenance procedures (e.g. maintenance manuals), configuration management (e.g. aircraft, engine and component configurations), training, flight operations (e.g. master minimum equipment list) and a flight crew operating manual (ATA). The FAA (Federal Aviation Administration) has made the ATA numbering system (ATA 100 Spec) mandatory (FAA), aiming to make aviation safer.

Similarly, aircraft manufacturers, such as Boeing, were able to force and direct the industry suppliers into wide adoption of their standards. For example: Boeing ensures that the same edition of the standard for geometric design is used by all partners involved in the design of the Dreamliner aircraft (Duvall and Bartholomew, 2007). It appears that in the aerospace industry, wide adoption was caused by enforcement by governmental/ safety bodies, and was aided to a large extent by the fact that the industry is dominated by just a few major aircraft manufacturers and airline associations, who are able to enforce or endorse the use of standards, even if they are proprietary. However, despite of this, further work is still required, for example of standardization of the flight operation manual (Bourgon).

iSpec2200 and S1000D

Besides iSpec2200 there is another prominent aerospace standard: S1000D, an international specification for technical publications, was initially developed by the AeroSpace and Defence Industries Association of Europe (S1000D). The functionality the standard is in principle comparable to that of iSpec2200. S1000D was initially designed for military aircraft while iSpec2200 is intended for commercial aircraft (CEN). However, the scope of S1000D was extended in the last years and is still evolving (including functionality for both military and civil products) and might even be used in e.g. the process industry (S1000D). It was also suggested that S1000D may replace iSpec2200 in the future (S1000D), (CEN).

One of the reported reasons (by CEN, (CEN)) is that S1000D is regarded more flexible when it comes to re-use of data. This might be due to the fact that iSpec2200 was designed from the needs of the end-user, based on the specifications of the technical publications (Greenough and Williams, 2007), whereas S1000D was designed with the integrated use of data in mind (CEN).

5.5.2 Automotive

Dreverman (Dreverman, 2005) and Haag and Vroom (Haag and Vroom, 1996) show that also the automotive industry has had considerable success in adopting asset information standards, such as STEP/ISO10303 AP214. Adoption of asset information standards in automotive happened primarily in procurement and engineering processes. The adoption in the automotive industry was accelerated by a requirements-driven approach from an aligned user community according to Haag and Vroom (Haag and Vroom, 1996) and Dreverman (Dreverman, 2005). In 1991, five German organizations in the automotive and electro-technical industry started ProSTEP: 'Development of Methods and Tools for Computer Aided Design and Production Facilities using STEP'. ProSTEP is an organization in which more than hundred European automotive companies jointly develop STEP standards.

This pressured software suppliers to participate in implementation forums (Dreverman, 2005). One of the most important requirements was (an information standard that would support) concurrent engineering (CE) (Haag and Vroom, 1996). Concurrent engineering is a systematic approach to the integrated, simultaneous design of both products and their related processes, including production. To use of CE effectively requires accuracy of data and a common architecture (Gunasekaran, 1998).

5.5.3 Comparison

It appears that the use of asset information standards is more developed in the aerospace and automotive industries than in the process industry. This is the reason why further research and implementation efforts have a high priority for leading standards consortia in the process industry, such as USPI (NL), POSCCaesar (Norway) and FIATECH (USA). Based on our preliminary findings, we have tried to compare causes for limited usage of the standards in the three industries.

One should realize that there are considerable differences in the industries and assets compared: the assets discussed in the automotive and aerospace industries are products, manufactured in series or through mass-production. The assets in the process industry are production plants, often developed or customized as one-of-a-kind, this means that the investment and return mechanisms may differ considerably. The way in which assets are produced also affects their variety. In the process industry, part of the assets (i.e. production installations) are one-offs, entirely engineered/ customized for the occasion. This may have affected the progress made in information modelling and exchange as the return on investment in information standards for parts and installations of which many are produced are much better than for one-off parts and installations even though process industry tries to use the knowledge from one installation to another. For this reason some progress was made with standards for specific components or sub-systems of process plants, the producers of which do try to standardize their processes (i.e. compressors, pumps, valves).

Secondly, due to the large numbers of companies involved, the process industry appears to lack dominant actors compared to the aerospace industry (Dreverman, 2005, Tolman, 1999), who could impose the adoption of asset information standards. An actor analysis of Dreverman (Dreverman, 2005) suggests that some actors in the process industry could perhaps stimulate the uniform adoption of asset information standards, but remain relatively passive, e.g. plant owners and software vendors. Also the estimated size of the investment to enforce one or more standards is seen to be as prohibitive for a single company (Dreverman, 2005). Dreverman (Dreverman, 2005) illustrates that plant owners should eventually become more active collectively in order to gain influence on e.g. engineering software companies, similar to the developments in the aerospace industry (Duvall and Bartholomew, 2007). Software vendors active in the process industry have not formed communities to agree on the use of standards (Dreverman, 2005). The problem is further aggravated by a diverse landscape of competing asset information standards. This makes it difficult for organizations in the process industry to make a choice for a specific standard and to invest in it.

A detailed comparison is summarised in Table 5.3. The summary is structured according to the aspects listed in the previous section, aspects related to the *organization,* to the *design of the standards,* and to the *business environment*.

	Process industries	Aerospace industries	Automotive industries
Use of Asset Information Standards	Initially reported momentum has not led to pervasive use of any standards throughout the industry (Fowler, 1995, Dreverman, 2005, Gielingh, 2008).	The aerospace industry is regarded as leading (Teeuw *et al.*, 1996). Some particularly successful standards, notably STEP/ISO10303 with AP210, AP203 AP232 and AP209 (Smith, 2002, PDES), S1000D(CEN), ATA 100 Spec, ATA 2100 Spec, iSpec 2200, S1000D.	The automotive industry has had considerable success in adopting asset information standards, such as STEP/ISO10303 AP214 (Dreverman, 2005, Haag and Vroom, 1996).
Organization			
Financial incentives	Difficulty in judging the benefits of integration, and the benefits of asset information standards (Gallaher *et al.*, 2002, Teeuw *et al.*, 1996, Gielingh, 2008).	Not based on a business case, but rather on enforcement by governmental regulatory bodies and dominant actors.	Not based on a business case, but rather on facilitation by an aligned community of key players and (later) software vendors.
Organizational readiness	Standards require understanding, preparation and discipline. This needs to be enforced (Gielingh, 2008, Van Exel, Wapakabulo *et al.*, 2005).	Standards adopted, enforced by governmental safety regulations (Lee *et al.*, 2007, Dreverman, 2005). Dominant actors, such as Boeing, are able to enforce the standards upon suppliers (Duvall and Bartholomew, 2007).	Adoption of standards driven by an aligned user community, developed from an initiative of five key players. Later software vendors started to offer the use of the standard as standard functionality (Gunasekaran, 1998, Dreverman, 2005, Haag and Vroom, 1996).
Standard design			
Development of asset information standards	Time-consuming development of standards has weakened commitment of sponsors and users (Tolman, 1999, Eisenberg and Melton, 1998).	Asset information standards such as iSpec2200 and S1000D were developed through commitment of dominant actors, e.g. aircraft builders and the cooperation of powerful bodies in aerospace e.g. ASD, AIA and ATA.	In automotive the standards development was accelerated by a requirements-driven approach from an aligned user community (Haag and Vroom, 1996).
Revisioning process/ stability of the standards	Newer version of the STEP/ISO10303 standard lack backward compatibility (Wapakabulo *et al.*, 2005).	Newer version of the STEP/ISO10303 standard lack backward compatibility (Wapakabulo *et al.*, 2005). S1000D provides users with tools to map older versions to newer versions(S1000D).	Newer version of the STEP/ISO10303 standard lack backward compatibility (Wapakabulo *et al.*, 2005).

Complexity of the standards	STEP/ISO 10303 and ISO15926 seen as very complex/ counterintuitive (Smith, 2006, Mathew *et al.*, 2006). Supporting software suppliers claim to reduce the complexity of the use of the standards (Siemens).	STEP/ISO10303 and ISO15926 seen as very complex/ counterintuitive (Smith, 2006, Mathew *et al.*, 2006). Supporting software suppliers claim to reduce the complexity of the use of the standards (Siemens).	STEP/ISO 10303 and ISO15926 seen as very complex/ counterintuitive (Smith, 2006, Mathew *et al.*, 2006). Supporting software suppliers claim to reduce the complexity of the use of the standards (Siemens).
Lack of accessibility to the standard	E.g. STEP/ISO 10303 requires licence fees. This may hinder pervasive use (Wapakabulo *et al.*, 2005, Smith, 2006).	E.g. STEP/ISO 10303 requires licence fees. This may hinder pervasive use (Wapakabulo *et al.*, 2005, Smith, 2006). Others, such as S1000D are provided free of charge (S1000D). The incorporation of standards, e.g. S1000d in Siemens PLM software (Siemens) diminishes the need for an end-user to access the original standard.	STEP/ISO 10303 AP214 requires license fees. This may hinder pervasive use (Wapakabulo *et al.*, 2005, Smith, 2006). Similarly to the aerospace industries the standards are incorporated in software packages, e.g. Catia which may lower the need for an end-user to have access to the original standard.
Quality of standards	Several ontological and other problems in e.g. ISO15926 (Smith, 2006).	The problems discussed for ISO15926 are partly also applicable to STEP/ ISO10303 AP214.	
Business environment			
Adoption in the industry	Lack of dominant actors or governmental bodies or industry communities enforcing the standards (Dreverman, 2005).	Standards adopted, enforced by governmental safety regulations (Lee *et al.*, 2007, Dreverman, 2005). Dominant actors are able to enforce the standards upon suppliers (Duvall and Bartholomew, 2007).	Adoption of standards driven by an aligned user community, developed from an initiative of five key players. Later software vendors started to offer the use of the standard as core functionality (Gunasekaran, 1998, Dreverman, 2005, Haag and Vroom, 1996).
Legal aspects	Potentially unclear liabilities in data exchange and the correct use of the standards (Gielingh, 2008). License to operate (Dreverman, 2005).	Managed as part of the above mentioned enforcement.	Managed as part of the above mentioned facilitation.

Table 5.3: Comparison between Process, Aerospace and Automotive industries, based on the literature

5.6 Summary, conclusions and research directions

Other researchers have already stressed the importance of the design and optimization of the plant and equipment in the process industry for operational performance when compared to discrete manufacturing. Designing a process plant is usually a multi-disciplinary activity, involving various engineering disciplines and suppliers. Also (continuously) optimizing a process plant tends to involve close cooperation between a number of disciplines and parties, including maintenance, design/engineering and equipment suppliers. Due to the often complex nature of the process plant and the multi-disciplinary nature of the design and optimization processes, successful exchange of plant design information between disciplines and parties is important for the success of the design and optimization processes, and hence for the operational performance.

Our exploratory investigation consists of a literature review and two case studies. The literature survey starts with providing a comprehensive overview of asset information standards (summarised in Table 5.2), categorised by semantic richness (Van Renssen, 2005), asset hierarchical class and the typical use of the standard.
The literature survey further shows that the process industry has had only limited success in introducing asset information standards, despite significant efforts. Since information hand-over between asset life cycle phases is important, lack of information standardisation suggests that collaboration costs are likely to be higher than necessary.
For the case studies, two organisations were selected which have relatively mature asset organisation management processes. The cases both showed implementations whereby firstly the standard was embedded internally, and also used in the communication with (external) partners. It was demonstrated that the first use and acceptance of a standard can be enhanced by a 'pragmatic approach', whereby local customisations of the standard are allowed. This does not help the external use of the standard.

Finally, the reported causes for the lack of pervasiveness were reviewed in a comparison between practices in the process industry and the aerospace and automotive industries.

Causes for (lack of) adoption of asset information standards in the process industry were grouped into standard related causes, organization related causes and environment related causes. These are summarized in Figure 5.2.

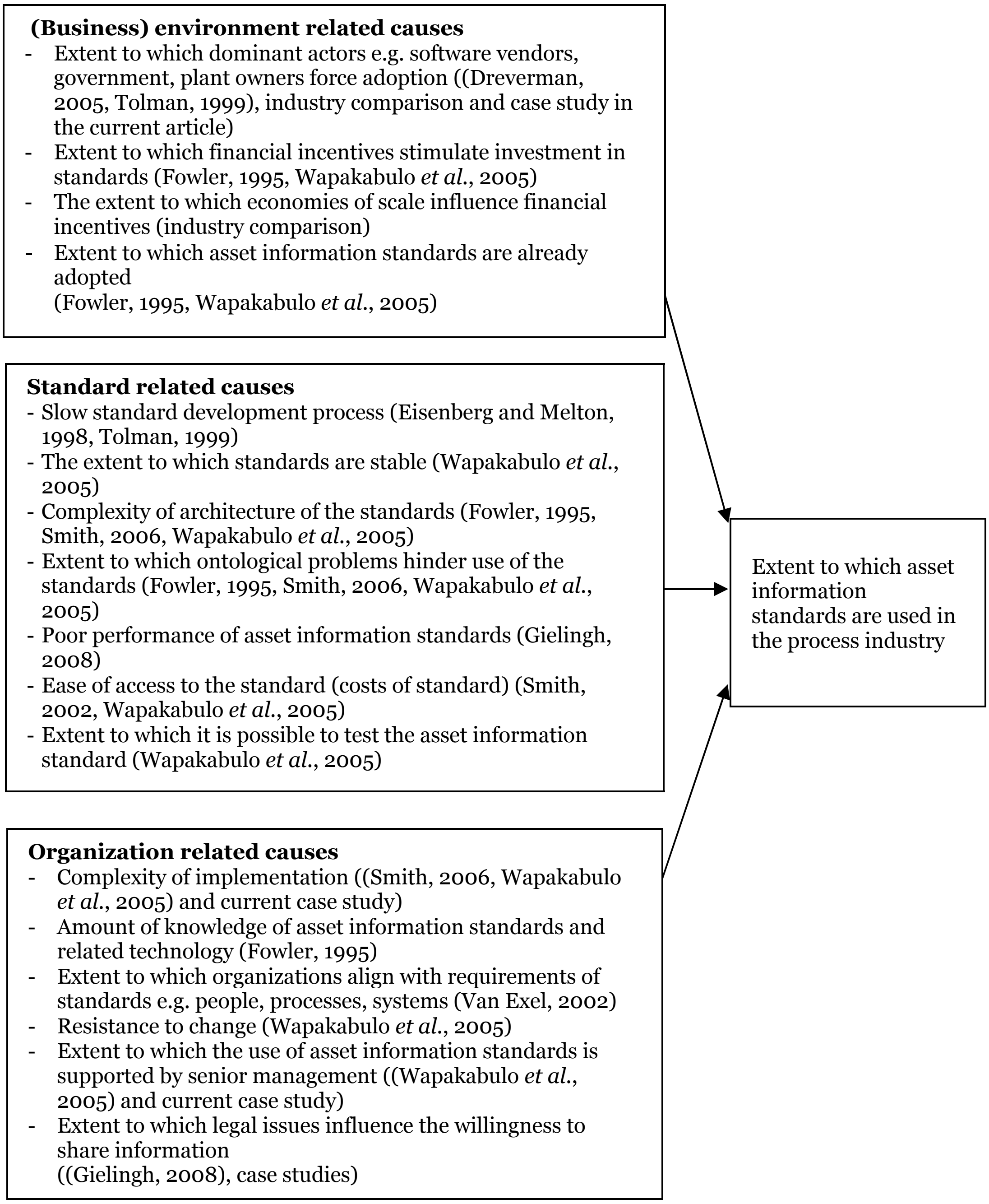

Figure 5.2: Causes for (lack of) adoption of asset information standards in the process industry

The insight into the causes for lack of use of asset information standards in the process industry is necessary for eventual success in adopting asset information standards.

In order to gain further in depth understanding of the possibilities to improve the current situation, it will be necessary to decide for each of the causes mentioned here to which extent they can be eliminated/ minimized. This leads to a number of conclusions and proposals for direction. Eliminating the environmental causes would require organizing governmental enforcement of the uniform use of the standards. Initiating and gaining momentum requires broad action. Governmental bodies may only be inclined to take such action if and it when it becomes apparent that the standardized regulations (and uniform use of standards) are feasible. This may require eliminating some of the other current causes for lack of adoption first.

It appears from the descriptions of the organization related causes that these are aggravated by the complexity of the standards (i.e. the complexity of the implementation, the extent to which expert knowledge is required and the perceived ease of use of the standard all are related to the complexity of the standard). In addition, it was reported that the only successful initiatives in the process industry so far make use of small, relatively limited standards, or small parts of larger standards.

The contribution of this chapter is insight into the use of asset information standards and the causes for lack of pervasiveness. This was made specific in the Figure 5.2 and Table 5.3, which could be used by practitioners and researchers to select and develop the use of asset information standards. This in turn is necessary for improving the collaboration in the process industry.

Research directions

Future research work should be focused on causes which hinder the pervasiveness of asset information standards, in particular the complexity of the asset information standards, since this is likely to also positively influence the other causes, as became apparent in the case studies.

This would entail two main research areas; first of all, e.g. the use of ISO15926 as a methodology (meta-concept), and secondly the automatic mapping different standards.

(1) *Use of ISO15926 as a methodology*: The currently available comprehensive standards designed for the process industry do constitute in theory all information relevant for successful and extensive collaboration in the process industry. The next step will be to investigate how e.g. ISO15926 can be used as a methodology (meta-concept) for designing and incorporating already available and successful smaller context specific standards (e.g. eCl@ss, Prolist/NE100, OSA-EAI/CBM and ISO14224). New standards should be developed in such a way that context specific standards are much easier to apply and enforce, while still being fully compliant with the 'parent-standard' ISO15926. The latter is of particular importance, since many new, small standards would otherwise be developed based on different principles and in different ways, instead of working towards having uniform work methods.

In our view, this way of development has the potential to enable the future adoption of uniform principles in asset information standards in the process industry. One could learn from successful examples of such developments in other industries, e.g. S1000D in the aerospace industry.

(2) *Automatic mapping of standards:* A second promising area for further work related to the standard related causes would be the automatic mapping of different asset information standards or versions of standards.

Acknowledgements
The authors wish to sincerely thank: members of USPI, members of CEN WS-ORCHID and of the ISOTC184/SC4 committee for their support to the study, Andries van Renssen of Shell Global Solutions for his support on Gellish fundamentals, Leo van Ruijven from Croon TBI Techniek for his support on the fundamentals of standards and the actual implementation in practice, Paul Casteleijn of Stork Asset Management Solutions for his guidance and support of the current research work, Ingrid van der Linde and Gerrit Misana of Stork GLT and Theo Horbach and Sybren Bakker of AkzoNobel Botlek. The authors also wish to thank the Editor-in-Chief and the reviewers of Computers in Industry for their excellent comments and effort.

Appendix 5:
Illustration of asset information standards

To illustrate asset information standards in maintenance processes, two asset information standards are illustrated. First of all an example of the KKS standard also used by a case company in chapter 2 and secondly the relatively all-encompassing ISO15926 standard which is still being further developed.

KKS

KKS is defined as Kraftwerk Kennzeichen System indicating process plant designation system and is mentioned as being widely used in Europe (Shamsuddin, 2004). The system provides method to identify plant equipment and its operation. It also covers the buildings and structures. The classification system is founded on function of equipment or component or a part. The number allocated by the KKS system to equipment is broken down into a number of levels, see table x1 for the breakdown levels and table x2 for level 1 function code examples. There is a field or set of fields within each level and each field occupies a letter or a number according to a convention. The classification and identifications of plant equipment is taken as an example in figure 5a.1.

KKS fields

Breakdown level	Plant Id	Unit No	Level 1 function					Level 2 equipment code					Level 3 components or signal			
Position code	G	F_0	F_1	F_2	F_3	F_n	F_n	A_1	A_2	A_n	A_n	A_3	B_1	B_2	B_n	B_n
Type of character	A or N	N*	A	A	A	N	N	A	A	N	N	N	A	A	N	N

Table 5a.1: Breakdown of Equipment in three levels, from function to equipment to components or signal (Shamsuddin, 2004)

KKS level 1 function code examples

A	Grid and distribution systems
B	Power transmission and auxiliary power supply
C	Instrumentation and control equipment
D	Not defined
E	Conventional fuels and supply and residue disposal
F	Handling of nuclear equipment
G	Water supply and disposal
H	Conventional i.e. mononuclear heat generation
J	Nuclear heat generation
K	Reactor auxiliary systems
L	Steam water and gas cycles
M	Main machine sets
N	Process energy, e.g. district heating
P	Cooling water systems
Q	Auxiliary systems, e.g. air compressors
R	Gas generation and treatment
S	Ancillary systems, e.g. heating and ventilation
U	Structures
W	Renewable energy plants
X	Large machines (not included in main machine sets)
Y	Not defined
Z	Workshop and office equipment

Table 5a.2: KKS level 1 function code examples (Shamsuddin, 2004)

Example for KKS breakdown level

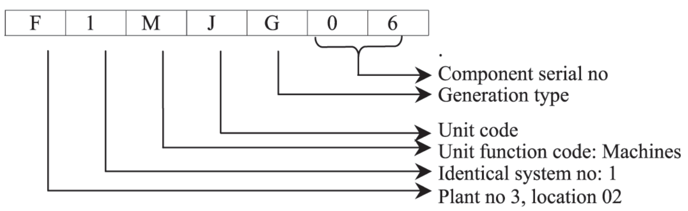

Figure 5a.1: Example for KKS breakdown (level 1) (Shamsuddin, 2004)

ISO15926

Another example is the ISO15926 standard or ontology for description of asset information. The standard is based on concepts of the earlier STEP/ISO10303 standard. The ISO15926 standard can be used for classification but can also be used for other purposes such as the geometric description of assets.

The following example shows the description of a pump by using the ISO15926 standard in the open and online accessible RDS/WIP library (2012).

The RDS/WIP library is a system for publishing definitions in ISO 15926 and related formalisms as a sort of collaboratively maintained library, using OWL/RDF and SPARQL for representing and querying the various volumes of data (RDS/WIP, 2012).With ISO15926 not only a physical object such as a pump can be classified but also be used for classification for other objects, for example molecules.

General

RDS/WIP URI	http://rdl.rdlfacade.org/data#R10310427332
Label	RECIPROCATING POWER PISTON PUMP
Description	A reciprocating power pump utilizing piston(s) driven by power from an outside source applied to the crankshaft of the pump.
Entity Type	http://dm.rdlfacade.org/data#ClassOfInanimatePhysicalObject

PCA Attributes

Identifier	RDS866294
Designation	RECIPROCATING POWER PISTON PUMP
Creation Date	1999.06.30
Creator	u20683
Status	Recorded
Note	derived from Hydraulic Institute Standards

Specialization

- RECIPROCATING POWER PUMP
  - RECIPROCATING PUMP
    - POSITIVE DISPLACEMENT PUMP
      - PUMP
        - ARTEFACT
          - INANIMATE PHYSICAL OBJECT
            - ISO-IS 15926-2 PHYSICAL OBJECT
              - ISO 15926-4 POSSIBLE INDIVIDUAL
                - ISO 15926-4 THING
          - ISO 15926-4 INANIMATE PHYSICAL OBJECT
            - ISO-IS 15926-2 ARRANGED INDIVIDUAL
              - ISO 15926-4 POSSIBLE INDIVIDUAL
                - ISO 15926-4 THING
        - INANIMATE PHYSICAL OBJECT
          - ISO-IS 15926-2 PHYSICAL OBJECT
            - ISO 15926-4 POSSIBLE INDIVIDUAL
              - ISO 15926-4 THING
    - RECIPROCATING EQUIPMENT ITEM
      - INANIMATE PHYSICAL OBJECT
        - ISO-IS 15926-2 PHYSICAL OBJECT
          - ISO 15926-4 POSSIBLE INDIVIDUAL
            - ISO 15926-4 THING

Chapter 6

Conclusion and discussion

This final chapter consists of the main conclusions and a discussion of the findings. The aim of this thesis was to contribute to the academic knowledge on asset information for FMEA-based maintenance. Four research themes were identified that address research questions that fill several gaps in current knowledge. In this section the main findings of the thesis will be discussed. Directions for further research and the societal relevance of the presented research are also discussed.

6.1 Main findings

In this first section the main findings of the research are discussed per chapter which all represent a chapter. Each chapter corresponds to a paper, published earlier or submitted for publication.

6.1.1 Failure Mode and Effects Analysis for maintenance planning: a multiple case study in the process industry

RO1: To what extent are a number of common assumptions on the use of Failure Mode and Effects Analysis for (preventive) maintenance supported by empirical evidence?

The contribution of chapter 2 is an empirical investigation of a number of assumptions on the use of FMEA for maintenance planning in the process industry. Contrary to the original proposals on RCM/FMEA, but in line with recent literature, the companies studied followed a pragmatic approach in which only the most critical assets are identified and analyzed. FMEA is in practice regarded as a one-off exercise because of several (information) related problems. Maintenance engineers tend to update the maintenance plan, using e.g. feedback from the maintenance operators, without reference to the original FMEA findings, which then become outdated.

In addition, the FMEA-procedure is hindered in practice by operational problems (e.g. lack of a clear procedure) and information management problems (e.g. inaccuracy in failure reporting, relevant information distributed across various systems).

6.1.2 A quantitative method for Failure Mode and Effects Analysis

RO2: How can the repeatability of the FMEA method be improved and the ability to continuously improve maintenance routines be developed?

In chapter 3 our contribution is the development of a procedure which can serve to support the traditional method of Failure Mode and Effects Analysis (FMEA) and improves the repeatability of FMEA.

The enhancement is aimed at strengthening the traditional method: expert judgment is supported by taking into account the use historical failure data. The primary application of the model is to use the estimated probability of failure occurrence, combined with the expected cost to list the assets in order of decreasing risk. This list can be used in the traditional FMEA analysis. Also the so-called Receiver Operating Characteristics (ROC) analysis is demonstrated, in which the estimated probabilities are used to determine a better corrective/ preventive maintenance policy, which may be expected to result in lowest costs.

6.1.3 Design of a Maintenance Feedback Analysis (MFA) method for continuous FMEA-based maintenance

RO3: What are requirements and design principles for continuous FMEA-based maintenance?

In chapter 4 the contribution is a further exploration of the context in which the FMEA is conducted and re-used. We concentrated on the problems relating to feedback and re-use of FMEAs. We therefore extended our previous case studies with one in-depth case study on FMEA-based information management and thereby acquired design requirements and design principles for continuous FMEA-based maintenance. Based on these design requirements and design principles we propose a Maintenance Feedback Analysis method extending the current RCM/FMEA approach.

6.1.4 A review of the use of asset information standards for collaboration in the process industry

RO4: What are the causes for the lack of pervasiveness of asset information standards in the process industry compared to the aerospace industry?

The contribution of chapter 5 is insight into the use of asset information standards and the causes for lack of pervasiveness. This is necessary for improving the use of standards in collaboration in the process industry in general and improving the exchange of asset information more specific.

Comparison of the process industry with the aerospace industry and our case study results show that the process industry appears to have had only limited success in introducing such standards so far, despite significant efforts. This is confirmed by our literature review. Since information hand-over between asset life cycle phases is important, lack of information standardization suggests that collaboration costs are higher than necessary. Reported causes for the lack of pervasiveness can be grouped into standard related causes (slow development of standards, stability, complexity, cost, quality/ontological problems), organization related causes (lack of direct financial incentives, organizational readiness and resistance to change) and business environment related causes (legal aspects, level of adoption, limited governmental enforcement and a lack of dominant actors in the process industry).

6.1.5 Contribution of the thesis as a whole

During this research a number of aspects related to asset information management, an important enabler of effective FMEA-based maintenance, are investigated and proposals for improvement are stipulated. For this purpose, insight was gained into the use of FMEA in the process industry (chapter 2) and into problems with information management for FMEA-based maintenance. Acquisition of data from the assets is not always regarded as a useful (or cost-effective) activity (Moubray, 1992, Smith and Hinchcliffe, 2004, Garg and Deshmukh, 2006), which in turn makes analysis, feedback and improvement very difficult. This stalemate situation needs to be resolved.

We therefore suggest two additions to the existing FMEA; a quantitative approach (chapter 3) and a Maintenance Feedback Method (chapter 4) based on the criticality of asset information which can help in pro-actively organizing feedback to earlier FMEAs.

And finally our study on the use of asset information standards (chapter 5) laid bare causes for the lack of pervasiveness of asset standards in the process industry, these insights can be used to improve the implementation and development of new and existing standards.

6.2 Directions for further research

In this section, directions for further research for the individual chapters and the research as a whole are discussed. The case study on the use of FMEA led to some assumptions about the use of FMEA and maintenance planning, which guided further research for other chapters/ parts in this thesis.

6.2.1 Failure Mode and Effects Analysis for maintenance planning: a multiple case study in the process industry

This study yields a number of opportunities for further research. The study first of all laid laid bare a fundamental problem related to the nature of the RCM/FMEA procedure: FMEA is regarded as a one-off exercise by four out of the six companies investigated. Closely associated are operational and information management problems, such as data quality problems, e.g. accuracy of (failure) registration, cost of information.

Future research should therefore be guided on the repeatability of FMEAs. In chapter 3 we present a quantitative method which improves the repeatability and continuous improvement of FMEAs.

To reduce efforts and improve return on investment the data collection of asset information may be focused on asset parts that have the highest 'criticality', a criticality based maintenance approach may be designed and used for this.

The focus on critical asset parts is used as a design principle in chapter 4 in which the Maintenance Feedback Analysis (MFA) method is presented. This method uses the determined criticality of assets to make a focused data collection effort possible.
In Chapter 5, we review the use of asset information standards which can help to improve data quality and the accuracy of (failure) registration.
Finally, this study might also be fruitfully applied in other industry segments outside the process industry as they also apply RCM/FMEA procedures.

6.2.2 A quantitative method for Failure Mode and Effects Analysis

The measurement of degradation is left for future research. In our approach, time and cross sections are taken as equal, i.e. all physical assets are assumed to be identical. However, if data for similar but different assets is available over a certain period, it is possible to relax this assumption. Consider the situation that assets have unobservable characteristics that cause differences in the failure rate (comparable to e.g. the problem of 'Monday morning products'). There is a way to cope with such unobservable characteristics by using a panel logistic model. It is possible to estimate the logistic model with e.g. fixed effects (Allison, 2009). We have not explored this further since it is outside of the scope of this chapter, but it may serve as suggestion for further research.

In a situation where failures are avoided, for example through Condition-based maintenance (CBM) (Veldman *et al.*, 2010), it may still be possible to use approximate failure data by assuming that failure would have happened if the condition-based maintenance actions would not have prevented it. Such combined CBM-FMEA routines are outside of the scope of this chapter.

In our model fixed time periods were used; future research could explore the influence of varying time periods and varying data sets on the results. In future research we aim to further investigate the relation between explanatory variables and asset failures in practice.

In addition, we discussed our model using fictitious cost-ratios. For future research it is suggested to test our model using a dataset with cost data. Finally, we suggest to do further work on testing with small sample sizes, as in practice, companies may only have limited data. Data improvement techniques may be relevant to improve the quality of the data in this respect. More extensive validation of the model could also be done by examining the out of sample performance of the model.

For the mentioned research directions, data collection is very important. In chapter 4 we propose a method which can be used to pro-actively identify asset information needs. The MFA analysis can be used to collect the needed data.

For data analysis, the exchange of data is very important. Standards can support these efforts. In chapter 5 we review the use of asset information standards in the process industry.

6.2.3 Design of a Maintenance Feedback Analysis (MFA) method for continuous FMEA-based maintenance

The presented MFA method might be contextually-sensitive (Wang and Hannafin, p. 6) as it is designed for use in the process industry. In further research the MFA method and design principles should be empirically tested in different contexts and if necessary improved. The presented method may be used as a starting point to develop better methods. The quality of (asset) information and its relationship with criticality and cost are proposed topics for further research, as better insight in this relationship can improve information feedback. Finally the exchange of asset information (e.g. semantic interoperability of asset information), very important for integration of various data sources deserves more extensive research. The exchange of asset information is also discussed in chapter 5.

6.2.4 A review of the use of asset information standards for collaboration in the process industry

Future research work should be focused on causes which hinder the pervasiveness of asset information standards, in particular the complexity of the asset information standards, since this is likely to also positively influence the other causes, as became apparent in the case studies.

This would entail two main research areas; first of all, e.g. the use of ISO15926 as a methodology (meta-concept), and secondly the automatic mapping different standards.

(1) *Use of ISO15926 as a methodology*: The currently available comprehensive standards designed for the process industry do constitute in theory all information relevant for successful and extensive collaboration in the process industry. The next step will be to investigate how e.g. ISO15926 can be used as a methodology (meta-concept) for designing and incorporating already available and successful smaller context specific standards (e.g. eCl@ss, Prolist/NE100, OSA-EAI/CBM and ISO14224). New standards should be developed in such a way that context specific standards are much easier to apply and enforce, while still being fully compliant with the 'parent-standard' ISO15926. The latter is of particular importance, since many new, small standards would otherwise be developed based on different principles and in different ways, instead of working towards having uniform work methods.

In our view, this way of development has the potential to enable the future adoption of uniform principles in asset information standards in the process industry. One could learn from successful examples of such developments in other industries, e.g. S1000D in the aerospace industry.

(2) *Automatic mapping of standards:* A second promising area for further work related to the standard related causes would be the automatic mapping of different asset information standards or versions of standards (van Blommestein, 2012).

6.3 Societal relevance

Our concepts to improve and standardize asset information and improve the accuracy of maintenance concepts can help to reduce maintenance cost and reduce safety margins. It is difficult to calculate the exact impact of these improvements, but given the significance of maintenance choices on operational excellence as well as health, safety and environment, the study may have a considerable impact.

The research project was conducted in close cooperation with the industry by multiple case studies. The results can be used in the process industry and have the potential to be made applicable to other industries as well, since in other industries RCM/FMEA concepts are also in use.

In this thesis the asset information is focused on the improvement of maintenance concepts in the maintenance phase, the same asset information can however also be used on other aspects of asset management, e.g. improving sustainability of assets and in other life-cycle phases (design and phase-out of assets).

Better assets will have a positive influence on economic growth and our welfare.

Samenvatting (Summary in Dutch)

Dit proefschrift is er op gericht te komen tot een verbeterde informatievoorziening over kapitaalgoederen ten behoeve van goed onderhoud en ten behoeve van gebruik van methodische onderhoudstechnieken. Onderhoud heeft een belangrijke rol in de bewaking van de integriteit van kapitaalgoederen en daarmee in de betrouwbaarheid, veiligheid en duurzaamheid van deze kapitaalgoederen. Deze thema's zijn van groot belang voor de samenleving.

Dit belang wordt ook duidelijk uit het bedrag dat jaarlijks aan onderhoud wordt gespendeerd. Volgens NVDO (2011) hebben de Nederlandse kapitaalgoederen een gezamenlijke waarde van 400 miljard euro. Jaarlijks wordt gemiddeld 4% van deze waarde uitgegeven aan het onderhoud hiervan, in de procesindustrie is dit zelfs gemiddeld 6%.

Het belang van goed onderhoud en de doelstelling om tot betere onderhoudstechnieken te komen en die te gebruiken is ook onderkend door Stork Technical Services, een grote Nederlandse maintenance contractor die dit onderzoek ondersteunt en zonder wie dit onderzoek niet tot stand zou zijn gekomen. Vanwege de karakteristieken van de procesindustrie, o.a. het relatief hoge bedrag dat wordt uitgegeven aan onderhoud en de focus van Stork Technical Services op de procesindustrie is er voor gekozen om het onderzoek op de procesindustrie te concentreren.

Voor onderhoud is een "maintenance concept" erg belangrijk. Een maintenance concept kan worden omschreven als het beleid of de benadering waarmee de hoeveelheid onderhoud en het type onderhoud voor een kapitaalgoed wordt bepaald. Bijvoorbeeld de keuze voor de hoeveelheid preventief onderhoud die jaarlijks wordt uitgevoerd. Een maintenance concept heeft in het verbeteren van eerdergenoemde doelstellingen daarom een belangrijk aandeel.

Eén van de bekende methodieken die wordt gebruikt om maintenance concepten te ontwikkelen is Reliability Centered Maintenance (RCM). Deze methodiek afkomstig uit de luchtvaart is gebaseerd op de criticaliteit van (onderdelen) van installaties. Een belangrijk aspect van deze methodiek is Failure Mode en Effects Analysis (FMEA), een methode waarin naast de wijze waarop een machine kan falen, de criticaliteit van een storing wordt bepaald. Deze informatie kan vervolgens gebruikt worden om een onderhoudsconcept te bepalen. Expertkennis is bij al deze afwegingen erg belangrijk.

Voor verbetering van een dergelijk onderhoudsconcept is herhaling van de RCM/FMEA methodiek en het leren uit opgedane ervaring erg belangrijk. In de praktijk blijkt dat de RCM/FMEA echter veelal éénmalig te worden toegepast: onderhoudsconcept wordt direct aangepast zonder naar de onderliggende (FMEA) onderbouwing van het bestaande onderhoudsconcept te kijken. Hieruit kan worden opgemaakt dat een groot aantal onderhoudsconcepten mogelijk niet optimaal zijn en dus verbeterd zouden kunnen worden. De omvang van deze verbeteringen zijn echter moeilijk in te schatten.

Er is een aantal informatiemanagement problemen die hier mee te maken hebben, o.a. de onzekerheid over de toekomstige informatiebehoefte, toegankelijkheid van kennis, kosten en complexiteit van het onderhouden van data, informatie overdrachtsproblemen tussen maintenance en engineering en een gebrek aan het gebruik van informatiestandaarden.
De onderzoeksdoelstelling van dit proefschrift is dan ook het management van informatie over kapitaalgoederen voor FMEA gebaseerd onderhoud te verbeteren. In verschillende hoofdstukken die ten dele ook gepubliceerd zijn als artikelen in een aantal wetenschappelijke tijdschriften gaan we in op verschillende onderzoeksvragen.

In hoofdstuk 2 wordt allereerst het gebruik van FMEA onderzocht in de procesindustrie, hierbij is er onderzocht in hoeverre een aantal aannames uit de literatuur over het gebruik van FMEA voor preventief onderhoud worden ondersteund door empirisch bewijs.
Uit dit eerste onderzoek blijkt dat bedrijven een pragmatische benadering volgen waarin alleen de meest kritieke kapitaalgoederen worden geïdentificeerd en geanalyseerd. Dit staat in tegenstelling tot de originele voorstellen voor RCM/FMEA, maar is in lijn met recente literatuur. Daarnaast wordt RCM/FMEA in de praktijk meestal gezien als een eenmalige exercitie, en niet als een methode die herhaald moet worden vanwege verschillende operationele problemen (bijv. gebrek aan een heldere procedure) en diverse informatieproblemen.

Deze informatieproblemen zijn de aanleiding om in verdere hoofdstukken ons te concentreren op herhaalbaarheid van de FMEA methodiek en de problematiek rondom informatie van kapitaalgoederen voor FMEA gebaseerd onderhoud.

In hoofdstuk 3 en hoofdstuk 4 worden twee methodieken voorgesteld waarmee de herhaalbaarheid van FMEA kan worden verbeterd. Deze methodieken kunnen beiden worden gecombineerd met de bestaande RCM/FMEA methodiek. Hoofdstuk 5 gaat in op de problemen rondom het gebruik van informatie standaarden voor kapitaalgoederen. Deze problemen beïnvloeden ook de informatie-uitwisseling en hierdoor uiteindelijk ook de analyse en feedback op de FMEA van de betreffende kapitaalgoederen.

In hoofdstuk 3 wordt onderzocht in hoeverre de herhaalbaarheid van FMEA met behulp van een kwantitatieve benadering kan worden verbeterd. Dit onderzoek leidt tot een kwantitatieve methode die als toevoeging op de bestaande FMEA methodiek kan worden gebruikt. De methode is gebaseerd op het gebruik van historische data en kan als ondersteuning of aanvulling gebruikt worden op de inhoudelijke inschatting door experts. De methode is gericht op het verminderen van de te verwachten kosten van storingen en onderhoud van een kapitaalgoed.

In hoofdstuk 4 wordt verder onderzocht wat de eisen en mogelijke ontwerp principes zijn om herhaaldelijk tot een verbeterd FMEA gebaseerd onderhoudsconcept te komen. We gaan hierbij in een aanvullende studie verder in op onze eerdere gevalstudies. Zo worden ontwerp eisen en ontwerp principes verkregen die kunnen worden gebruikt voor continue FMEA gebaseerd onderhoud. Gebaseerd op deze ontwerpeisen en ontwerp principes stellen we een Maintenance Feedback Analyse methode voor die de huidige RCM/FMEA methodiek uitbreidt.

In hoofdstuk 5 worden oorzaken voor het gebrek aan verspreiding van kapitaalgoed informatiestandaarden in de procesindustrie ten opzichte van de luchtvaart onderzocht. Dit is noodzakelijk om het gebruik van standaarden voor de samenwerking in de procesindustrie in het algemeen te begrijpen en om het verbeteren van kapitaal goed standaarden voor informatie uitwisseling meer specifiek te kunnen beschrijven.

Hoofdstuk 5 is gebaseerd op literatuuronderzoek en op een gevalstudie. In ons literatuuronderzoek is een vergelijking gemaakt tussen de procesindustrie en de luchtvaart industrie. Onze gevalstudie toont dat de proces industrie tot nu toe een beperkt succes in het introduceren van standaarden lijkt te hebben gehad ondanks significante inspanningen.

Gerapporteerde oorzaken voor het gebrek aan verspreiding van standaarden kunnen worden gegroepeerd in:

- Oorzaken gerelateerd aan de standaard (trage ontwikkeling van standaarden, stabiliteit, complexiteit, kosten, kwaliteit / ontologische problemen),
- Organisatorische problemen (gebrek aan financiële stimuli, organisatorische gereedheid en weerstand tegen verandering) en
- Oorzaken, gerelateerd aan de bedrijfsomgeving (juridische aspecten, niveau van adoptie, beperkte overheidsdruk en een gebrek aan dominante actoren in de procesindustrie).

Omdat de informatie overdracht tussen verschillende levenscyclus fasen belangrijk is, suggereert een gebrek aan informatiestandaardisatie dat informatie uitwisselingskosten hoger zijn dan noodzakelijk.

Toekomstig onderzoek zou moeten worden gericht op het verbeteren en testen van de voorgestelde kwantitatieve methode, o.a. met verschillende data en de MFA methode. Voor verbeterde data analyse is het nodig onderzoek te doen naar de kwaliteit en kosten van kapitaalgoed informatie. Als laatste is er onderzoek naar standaarden nodig die de uitwisseling van kapitaalgoed informatie vereenvoudigen en daarmee ook de feedback op bestaande onderhoudsconcepten kan verbeteren.

In zijn totaliteit geeft het uitgevoerde onderzoek diverse aanknopingspunten voor het verbeteren van kapitaalgoed informatie en voor het met behulp van RCM/FMEA verbeteren van onderhoudsconcepten.

De toepasbaarheid van de voorgestelde methodieken en concepten zijn niet beperkt tot gebruik binnen de RCM. De voorgestelde methodieken en concepten worden toegepast voor andere op FMEA gebaseerde methodieken. Daarnaast kan het onderzoek door het generieke karakter van de uitkomsten zeer waarschijnlijk ook in andere industrieën worden toegepast. Ook is het onderzoek toepasbaar buiten de operatie en onderhoudsfase. Zoals in de ontwerpfase waarmee structurele verbeteringen aan kapitaalgoederen mogelijk worden.
Het onderzoek draagt hierdoor bij aan effectievere productiemiddelen. Dit zorgt op zijn beurt weer voor een effectievere en efficiëntere productie, wat goedkopere productie en welvaartsgroei kan bewerkstelligen.

Dankwoord

Promoveren kun je niet alleen, er zijn veel mensen die hebben bijgedragen aan de totstandkoming van dit proefschrift en die ik daar dan ook voor wil bedanken.
Een belangrijke rol in de start van mijn promotie hebben Egon Berghout en Arnold Commandeur gehad waar ik voor een afstudeerstage bij UWV door werd begeleid. Dankzij hun inspanningen en enthousiasme over promoveren en onderzoek kwam ik in contact met Hans Wortmann en Warse Klingenberg.

Hans Wortmann is voor mij als promotor erg belangrijk geweest, zijn ideeën en enthousiasme voor onderzoek in de volle breedte motiveerden mij altijd om steeds een volgende slag te maken. Gerard Gaalman mijn tweede promotor had een meer vaderlijke rol. Hij leerde me aandacht en precisie te hebben en dat ook na vele reviews een onderzoek nooit af is. Iets wat me heeft leren focussen op de echt belangrijke zaken in mijn onderzoek.

Met Warse Klingenberg mijn co-promotor heb ik het meest intensief samengewerkt. Van hem heb ik de fijne kneepjes van het onderzoek geleerd. Warse wil ik dan ook bedanken voor zijn jarenlange inzet en ondersteuning. Door hem heb ik de schoonheid van een zorgvuldig geformuleerde zin of alinea leren waarderen.

Dit proefschrift zou niet tot stand zijn gekomen zonder de bijdrage van Stork Technical Solutions. Stork heeft mijn onderzoek financieel ondersteund en ook toegang gegeven tot de kennis van veel verschillende medewerkers die ik allen wil bedanken voor hun inzet. Eén daarvan wil ik in het bijzonder noemen, Paul Casteleijn. Hij nam de tijd om zijn jarenlange ervaringen op het gebied van onderhoudsmanagement actief met mij te delen. Zo leerde ik ook door de bril van het bedrijfsleven naar onderhoud te kijken en zo de relevantie van mijn onderzoek te verhogen. Samen met Paul van Exel was hij één van de belangrijkste inspiratiebronnen voor mijn onderzoek.

Paul van Exel, directeur van USPI, heeft mij de wereld van standaardisatie laten zien. Een wereld waarin het bereiken van consensus essentieel is. Paul leerde me hoe je mensen hiervoor samenbrengt en wat het belang van bestuurlijke processen is in de besluitvorming.

Tijdens mijn promotie zijn er veel bijzondere mensen op mijn pad gekomen zoals Aljar Meesters, Jasper Veldman, Chris Hicks, Tiedo Tinga en Leo van Dongen, die elk op eigen wijze bij hebben gedragen aan mijn promotie en ook mijn verdere carrière hebben beïnvloed.

Mijn collega's en mede PhD's wil ik bedanken voor alle borrels en koffiemomenten waarbij soms wel en vaak ook niet over de voortgang in het onderzoek werd gesproken. Mede dankzij hun is het een erg leuke tijd geworden. Samen met Boyana heb ik met veel plezier deel uit gemaakt van de SOM PhD commissie, waar we samen de gekste dingen georganiseerd voor de PhD collega's. Boyana leerde me dat een goede PR en enthousiasme erg belangrijk is voor het succes van iets wat je organiseert. Daarnaast heb ik aan haar een goede vriendin overgehouden.

De belangrijkste persoon in mijn promotie en die mij altijd heeft gesteund door dik en dun is mijn lieve vrouw Petra. Door haar werd ik altijd gemotiveerd door te gaan en ook positief terug te kijken naar wat al bereikt was.

Zonder afleiding is het moeilijk om altijd door te gaan, mijn vrienden hebben er voor gezorgd dat ik me weer op kon laden.

Ik wil ook alle personen en bedrijven bedanken die hun tijd beschikbaar hebben gesteld om mee te werken aan het onderzoek maar welke ik hier niet met naam heb genoemd.

Bij deze wil ik natuurlijk ook mijn paranimfen Jeroen en Boyana bedanken.

Maar zonder mijn ouders, mijn zus en familie was ik nooit zo ver gekomen, zij zijn het geweest die er voor hebben gezorgd dat ik deze stap in mijn leven kon maken. Zij hebben me altijd actief gesteund en waren er altijd positief over dat ik mijn doelen zou kunnen bereiken.

Bibliography

Allison, P. D., 2009. *Fixed effects Regression Models,* Newbury Park CA: Sage.

Arts, R., Knapp, G. & Mann, L., 1998. Some aspects of measuring maintenance performance in the process industry. *Journal of Quality in Maintenance Engineering,* 4 (1), 6-11.

ATA, iSpec2200: information standards for Aviation Maintenance, Publications ATA.

August, J. K., 2003. *RCM guidebook: building a reliable plant maintenance program*, PennWell Books.

Azadeh, A., Ebrahimipour, V. & Bavar, P., 2010. A fuzzy inference system for pump failure diagnosis to improve maintenance process: The case of a petrochemical industry. *Expert Systems with Applications,* 37 (1), 627-639.

Bahill, A. T. & Gissing, B., 1998. Re-evaluating systems engineering concepts using systems thinking. *IEEE Transactions on Systems, Man and Cybernetics Part C - Applications and Reviews,* 28 (4), 516-527.

Bellatreche, L., Dung, N. X., Pierra, G. & Hondjack, D., 2006. Contribution of ontology-based data modelling to automatic integration of electronic catalogues within engineering databases. *Computers in Industry,* 57, 711-724.

Bengtsson, M., 2004. Condition Maintenance System Technology - Where is Development Heading? *17th European Maintenance Congress 11th-13th of May 2004.*

Bertolini, M., Bevilacqua, M. & Mason, G., 2006. Reliability design of industrial plants using Petri nets. *Journal of Quality in Maintenance Engineering,* 12 (4), 397-411.

Bever, 2012. Open O & M and Mimosa Standards introduction. Mimosa.

Blanchard, B. S. & Fabrycky, W. J., 1998. *Systems Engineering and Analysis,* Upper Saddle River, NJ, Prentice-Hall.

Bloom, N. B., 2006. *Reliability Centered Maintenance - Implementation made simple*, McGraw-Hill.

Bourgon, L., Flight Operations Data, Air Transport Association Flight Operations Working Group.

Braaksma, A. J. J., Klingenberg, W. & van Exel, P. H. W. M., 2011. A review of the use of asset information standards for collaboration in the process industry. *Computers in Industry,* 62 (3), 337-350.

Braaksma, A. J. J., Klingenberg, W. & Veldman, J., 2012a. Failure Mode and Effects Analysis in asset maintenance: a multiple case study in the process industry. *International Journal of Production Research,* in press.

Braaksma, A. J. J., Meesters, A. J., Klingenberg, W. & Hicks, C., 2012b. A Quantitative method for Failure Mode and Effects Analysis. *International Journal of Production Research,* in press.

Braverman, J. I., Miller, C. A., Hofmayer, C. H., Ellingwood, B. R., Naus, D. J. & Chang, T. Y., 2004. Degradation assessment of structures and passive components at nuclear power plants. *Nuclear Engineering and Design,* 228 (1-3), 283-304.

BS5760, 2009. Part 5, page 3. *BS5760.* British Standards Institution.

BSI, 2006. BS EN 60812:2006. *Analysis techniques for system reliability. Procedure for failure mode and effects analysis (FMEA).* BSI.

Burgess, T. F., McKee, D. & Kidd, C., 2005. Configurations management in the aerospace industry: a review of industry Practice. *International Journal of Operations & Production Management,* 25 (3), 290-301.

Cameron, A. C. & Trivedi, P. K., 2005. *Microeconometrics: Methods and Applications,* New York, Cambridge University Press.

CEN, Recommendations on best practice standards for Life Cycle Technical Documentation, CEN/WS010/EG14.

Chang, G.-S., Perng, H.-L. & Juang, J.-N., 2008. A review of systems engineerings standards and processes. *Journal of Biomechatronics Engineering,* 1 (1), 71-85.

Cohen, J., 1988. *Statistical Power Analysis for the Behavioral Sciences,* Mahwah, NJ, Lawrence Erlbaum Associates.

Cox, J. F. & Blackstone, J. H., 1995. *APICS Dictionary,* Falls Church, American Production and Inventory Control Society.

Dennis, D. & Meredith, J., 2000. An Empirical Analysis of Process Industry Transformation Systems. *Management Science,* 46 (8), 1085-1099.

Dieter, G., 2000. *Engineering Design A Materials and Processing Approach*, McGraw-Hill.

Dittmann, L. U., 2006. OntoFMEA - Ontologiebasierte Fehlermöglichkeitsund Einflussanalyse.

DoD, 1980. MIL-STD 1629A. *Procedures for performing a failure mode, effects and criticality analysis.* Washington, Department of Defense USA.

Dongen, L. v., 2011. *Maintenance Engineering: Instandhouding van verbindingen*, University of Twente.

Dow, J. K. & Endersby, J. W., 2004. Mutinomial probit and mutinomial logit: a comparison of choice models for voting research. *Electoral Studies,* 23, 107-122.

Down, M., Brozowski, L. & Younis, H., 2008. *Potential failure mode and effects analysis (FMEA)*, Chrysler LLC, Ford Motor Company, General Motors Corporation

Dreverman, M., 2005. Adoption of product model data standards in the process industry, A comparative study into differences in the speed of adoption of product model data standards in the various industry sectors. Eindhoven, Technical University of Eindhoven.

Dul, J. & Hak, T., 2008. *Case study methodology in business research,* Amsterdam, Butterworth-Heinemann.

Duvall, M. & Bartholomew, D., 2007. PLM: Boeing's Dream, Airbus' Nightmare. *Baseline the project management center.*

Edelson, D. C., 2002. Design Research: What we learn when we engage in design. *Journal of the Learning Sciences,* 11 (1), 105-121.

Eisenberg, A. & Melton, J., 1998. Standards in practice. *SIGMOD Record,* 27 (3), 53-58.

Eisenhardt, K. M., 1989. Building Theories from Case Study Research. *Academy of Management Review,* 14 (4), 532-550.

Eisenhardt, K. M. & Graebner, M., 2007. Theory building from cases: opportunities and challenges. *Academy of Management Journal,* 50 (1), 25-32.

FAA, Minimum equipment requirements for general aviation operations under far part 91, Advisory Circular, 1991.

Fawcet, T., 2006. An introduction to ROC analysis. *Pattern Recognition Letters,* 27 (8), 861-874.

Fowler, J., 1995. *STEP: For data management exchange and sharing,* Twickenham, Technology Appraisals Ltd.

Franceschini, F. & Galetto, M., 2001. A New Approach for Evaluation of Risk Priorities of Failure Modes in FMEA. *International Journal of Production Research,* 39 (13), 2991-3002.

Fransoo, J. C. & Rutten, W. G. M. M., 1994. A typology of Production Control situations in Process Industries. *International Journal of Operations & Production Management,* 14 (12), 47-57.

Gabbar, H. A., Yamashita, H., Suzuki, K. & Shimada, Y., 2003. Computer-aided RCM-based plant maintenance management system. *Robotics and Computer Integrated Manufacturing,* 19 (5), 449-458.

Gallaher, M. P., O'Connor, A. C., Dettbarn, J. L. & Gilday, L. T., 2002. Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. National Institute of Standards and Technology (NIST).

Garg, A. & Deshmukh, S. G., 2006. Maintenance management: literature review and directions. *Journal of Quality in Maintenance Engineering,* 12 (3), 205-238.

Gielingh, W., 2008. An assessment of the current state of product data technologies. *Computer Aided Design,* 40 (7), 750-759.

Gnanadesikan, R. & Kettenring, J. R., 1972. Robust estimates, residuals, and outlier detection with multiresponse data. *Biometrics,* 28, 81-124.

Gorjian, N., L., M., Mittinty, M., Yarlagadda, P. & Sun, Y., 2009. A review on degradation models in reliability analysis. *Proceedings of the 4th WOrld Congress on Egineering Asset Management.* Athens, Greece.

Greenough, R. M. & Williams, D., 2007. Investigating the transfer of techniques for electronic technical support documentation from aerospace to machine tools. *International Journal of Advanced Manufacturing Technology,* 32, 774-779.

Gunasekaran, A., 1998. Concurrent Engineering: A competitive Strategy for Process Industries. *Intelligent management Systems in Operations,* 49 (7), 758-765.

Haag, E. & Vroom, R. W., 1996. The application of STEP in the automotive supply chain. *Computers in Industry,* 31 (3), 223-234.

Haarman, M. & Delahay, G., 2005. *VDM (Value Driven Maintenance) Nieuw geloof in onderhoud*, Mainnovation.

Hair, Black, Babin, Anderson & Tathan, 2006. *Multivariate Data Analysis*, Pearson / Prentice Hall.

Hevner, A. R., March, S. T., Park, J. & Ram, S., 2004. Design Science in Information Systems Research. *MIS Quarterly,* 28 (1), 75-105.

Holmström, J., Ketokivi, M. & Hameri, A. P., 2009. Bridging Practice and Theory: a Design Science Approach *Decision Sciences,* 40 (1), 65-87.

Hu, H., Cheng, G., Li, Y. & Tang, Y., 2009. Risk-based maintenance strategy and its applications in a petrochemical reforming reaction system. *Journal of Loss Prevention in the Process Industries,* 22 (4), 392-397.

IEC, 1985. IEC 60812. *Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA).* Geneva, International Electrotechnical Commission.

IEC/ISO, Enterprise-control system integration, IEC62264-2, 2004-2007.

INCOSE, Board of Directors, Annual Operating Plan, Release 1.2, January 2009.

INCOSE, Fellows Consensus on Systems Engineering.

ISO, 2006. ISO14224, Petroleum, petrochemical and natural gas industries - collection and exchange of reliability and maintenance data.

Johnston, J. & DiNardo, J., 1997. *Econometric Methods*, McGraw-Hill.

Kannengieser, U. & Gero, J. S., 2007. Agent-based interoperability without product model standards. *Computer-Aided Civil and Infrastructure Engineering,* 22 (2), 80-97.

Kans, M., 2008. An approach for determining the requirements of computerised maintenance management systems. *Computers in Industry,* 59 (1), 32-40.

Ketokivi, M. & Jokinen, M., 2006. Strategy, uncertainty, and the focused factory in international process manufacturing. *Journal of Operations Management,* 24 (3), 250-270.

Kmenta, S. & Ishii, K., 2000a. Scenario-based FMEA. *Proceedings of Design Engineering Technical Conference, Baltimore, Maryland.*

Kmenta, S. & Ishii, K., 2000b. Scenario-based FMEA: a life cycle cost perspective. *Design Engineering Technical Conference DETC 2000.* Baltimore, Maryland.

Lee, S. G., Ma, Y.-S., Thimm, G. L. & Verstraeten, J., 2007. Product lifecycle management in aviation maintenance, repair and overhaul. *Computers in Industry,* 59 (2-3), 296-303.

Leger, J.-B., Iung, B., Ferro De Beca, A. & Pinoteau, J., 1999. An innovative approach for new distributed maintenance system: application to hydro plants of the REMAFEX project. *Computers in Industry,* 38 (2), 131-148.

Li, L., Wu, B. & Yang, Y., 2005. Agent-based Ontology Integration for Ontology-based Applications. IN Meyer, T. & Orgun, M. (Eds.) *Australasian Ontology Workshop (AOW 2005).* Sydney, Australia, Conferences in Research and Practice in Information Technology (CRPIT).

Long, J. S., 1997. *Regression Models for Categorical and Limited Dependent Variables,* Thousand Oaks, CA, SAGE Publications, Inc.

Mathew, A., Zhang, L., Zhang, S. & Ma, L., 2006. A review of the Mimosa OSA-EAI Database for Condition Monitoring Systems. *The 1st World Congress on Engineering Asset Management (WCEAM2006).* 1st ed. Gold Coast, Australia.

McCutcheon, D. & Meredith, J., 1993. Conducting case study research in operations management. *Journal of Operations Management,* 11 (3), 239-256.

McDermott, R. E., Mikulak, R. J. & Beauregard, M. R., 2009. *The basics of FMEA,* New York, CRC Press.

Meredith, J., 1987. Automating the factory: theory versus practice. *International Journal of Production Research,* 25 (10), 1493-1510.

Meredith, J., 1998. Building operations management theory through case and field research. *Journal of Operations Management,* 16 (4), 441-454.

Mimosa, Mimosa, An Operations and Maintenance Information Open Systems alliance - brochure.

Mitchell, J. S. & Carlson, J., 2001. Equipment asset management - what are the real requirements? *Reliability magazine*.

Mobley, R. K., 2004. *Maintenance Fundamentals,* Oxford, Elsevier Butterworth-Heinemann.

Mobley, R. K. & Smith, R., 2002. *Maintenance Engineering Handbook*, McGraw-Hill.

Moubray, J., 1992. *Reliability-centered Maintenance*, New York: Industrial Press Inc.

Negandhi, A. R. & Reimann, B. C., 1973. Correlates of Decentralization: Closed and Open Systems Perspectives. *Academy of Management Journal,* 16 (4), 570-582.

Nemes, S., Jonasson, J. M., Genell, A. & Steineck, G., 2009. Bias in odds ratios by logistic regression modelling and sample size. *BMC Medical Research Methodology,* 9 (56), 1-5.

Nie, J., Braverman, J. I., Hofmayer, C. H., Choun, Y.-S., Kim, M. K. & Choi, I.-K., 2008. Identification and Assessment of Recent Aging-Related Degradation Occurrences in U.S. Nuclear Power Plants - Annual Report for Year 1 Task. *Joint Development of Seismic Capability Evaluation Technology for Degraded Structures and Components*. Brookhaven National Laboratory.

Nie, J., Braverman, J. I., Hofmayer, C. H., Choun, Y.-S., Kim, M. K. & Choi, I.-K., 2009. Identification and Assessment of Recent Aging-Related Degradation Occurrences in U.S. Nuclear Power Plants - Annual Report for Year 2 Task. *Joint Development of Seismic Capability Evaluation Technology for Degraded Structures and Components*. Brookhaven National Laboratory.

Nowlan, F. S. & Heap, H. F., 1978. *Reliability Centred Maintenance,* San Fransisco, United States Airlines Publications.

NVDO, 2011. *NVDO Onderhoudskompas, Visie, Trends en Ontwikkelingen,* Houten, NVDO.

PDES, STEP Sucess Stories (2006).

Picknell, J. V., 1999. The Reliability Handbook, Chapter 3: Is RCM the right tool for you? *PEM Plant Engineering and Maintenance,* 23 (6), 23-36.

Pot, R., 2007. Onderzoek naar Condition-Based Maintenance op basis van procesdata bij Stork GLT. *Business & ICT*. Groningen, University of Groningen.

RDS/WIP, 2012. RDS/WIP 1.0 library. *http://rdswip.ids-adi.org/presentation/overview/index.html*.

Rhee, S. J. & Ishii, K., 2003. Using cost based FMEA to enhance reliability and serviceability. *Advanced Engineering Informatics,* 17, 179-188.

Rhodes, D., INCOSE Long range plan, Release February 2005.

Riezebos, J., Klingenberg, W. & Hicks, C., 2009. Lean Production and information technology: Connection or contradiction? *Computers in Industry,* 60 (4), 237-247.

Rosqvist, T., Laakso, K. & Reunanen, M., 2009. Value-driven maintenance planning for a production plant. *Reliability Engineering and System Safety,* 94 (1), 97-110.

S1000D, S1000D & Industry, The impact S1000D on industry.

SAE, 2002. Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA).

Schuman, C. A. & Brent, A. C., 2005. Asset life cycle management: towards improving physical asset performance in the process industry. *International Journal of Operations & Production Management,* 25 (6), 566-579.

Schuman, C. A., Brent, A.C., 2005. Asset life cycle management: towards improving physical asset performance in the process industry. *International Journal of Operations & Production Management,* 25 (6), 566-579.

Selvik, J. T. & Aven, T., 2011. A framework for reliability and risk centered maintenance. *Reliability Engineering and System Safety,* 96 (2), 324-331.

Seyed-Hosseini, S. M., Safaei, N. & Asgharpour, M. J., 2006. Reprioritization of failures in a system failure mode and effects analysis by decision making trial and evaluation laboratory technique. *Reliability Engineering and System Safety,* 91 (8), 872-881.

Shamsuddin, A., 2004. Classification standards in large process plants for integration with robust database. *Industrial Management & Data Systems,* 104 (8), 667-673.

Sharma, R. K. & Sharma, P., 2010. System failure behavior and maintenance decision making using, RCA, FMEA and FM. *Journal of Quality in Maintenance Engineering,* 16 (1), 64-88.

Shell, 1996. Benefits of STEP. *Shell Information Services Report.*

Siemens, PLM-driven S1000D, Extending the capabilities of S1000D in a joint PLM-CMS environment, white paper, Siemens.

Sietinga, W., Schoen, P. & Davies, P., 2008. Renovation and Maintenance of the Groningen Gas Field, Descriptions and Learnings. IN Klingenberg, W. (Ed.) *NAM/StorkGLT Internal Report*.

Siggelkow, N., 2007. Persuasion with case studies. *Academy of Management Journal,* 50 (1), 20-24.

Siltanen, P. & Pärnänen, A., 2006. Comparison of data models for plant lifecycle information management. IN Ghodous, P., Dieng-Kuntz, R. & Loureiro, G. (Eds.) *Leading the web in concurrent engineering, Next generation concurrent engineering*. IOS Press.

Silva, N., Maio, P. & Rocha, J., 2005. An approach to ontology mapping negotation. *K-CAP 2005*. Banff, Canada.

SINTEF, 2002. *OREDA handbook,* Trondheim, OREDA participants.

Smith, B., 2006. Against idiosyncrasy in Ontology Development. IN Bennett, B. & Fellbaum, C. (Eds.) *Formal Ontology and Information Systems (FOIS 2006)*. Baltimore.

Smith, G. L., 2002. Utilization of STEP210 at the Boeing Company. *Computer Aided Design,* 34 (14), 1055-1062.

Smith, M. & Hinchcliffe, G. R., 2004. *RCM-Gateway World Class Maintenance,* Oxford, Elsevier Butterworth-Heinemann.

Soh, C. & Markus, M. L., 1995. How IT creates business value: a process theory synthesis. IN Ariav, G., Beath, C., DeGross, J. I., Hoyer, R. & Kemerer, C. (Eds.) *Proceedings of the 16th International Conference on Information Systems*. Amsterdam, The Netherlands, ACM.

Stamatis, D. H., 2003. *Failure mode and effect analysis: FMEA from theory to execution*, Quality Press.

Stavenuiter, J., 2002. Cost Effective Management Control of Capital Assets - an integrated Life Cycle Management Approach, Ph. D. Thesis. Delft University of Technology.

Summers, A. E., 1998. Techniques for assigning a target safety integrity level. *ISA Transactions,* 37 (2), 95-104.

Tan, J. & Kramer, M., 1997. A general framework for preventive maintenance optimization in chemical process operations. *Computers and Chemical Engineering,* 21 (12), 1451-1469.

Teeuw, W. B., Liefting, J. R., Demkes, R. H. J. & Houtsma, M. A. W., 1996. Experiences with product data interchange: On product models, integration and standardization. *Computers in Industry,* 31 (3), 205-221.

Teng, S. H. & Ho, S. Y., 1996. Failure mode and effects analysis - An integrated approach for product design and process control. *International Journal of Quality & Reliability Management,* 13 (5), 8-26.

Teoh, P. C. & Case, K., 2005. An Evaluation of Failure Modes and Effects Analysis Generation Method for Conceptual Design. *International Journal Computer Integrated Manufacturing,* 18 (4), 279-293.

Tolman, F. P., 1999. Product modeling standards for the building and construction industry: Past, present and future. *Automation in construction,* 8 (3), 227-235.

Tsang, A. H. C., 2002. Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering,* 8 (1), 7-39.

Tsang, A. H. C., Yeung, W. K., Jardine, A. & Leung, B. P. K., 2006. Data Optimization for CBM optimization. *Journal of Quality in Maintenance Engineering,* 12 (1), 37-51.

UMD, 2010. FMECA/FMEA Programs. University of Maryland.

Urban, S. D. & Rangan, R., 2004. From Engineering Information Management (EIM) to Product Lifecycle Management (PLM), guest editorial. *Journal of Computing and Information Science in Engineering,* 4 (4), 279.

Van Aken, J. E., 2004. Management Research based on the paradigm of the Design Sciences: The quest for flied-tested and grounded technological rules. *Journal of Management Studies,* 41 (2), 219-246.

van Blommestein, F., 2012. Teaching Business Systems to Agree

Natural Language Processing and Information Systems. IN Bouma, G., Ittoo, A., Métais, E. & Wortmann, H. (Eds.). Springer Berlin / Heidelberg.

Van Donk, D. P. & Fransoo, J. C., 2006. Editorial - Operations management research in process industries. *Journal of Operations Management,* 24 (3), 211-214.

Van Exel, P. W. H. M., Various documents about standardization in the process industry. USPI.

Van Exel, P. W. H. M., 2002. Reaching the process industry vision, roadmap to competitive advantage via sharing and storing plant lifecycle data. *Branch report.* USPI.

Van Renssen, A., 2005. Gellish, a Generic Ontological Language - Design and Application of a Universal Data Structure.

Veenman, A. & Besselink, L., 2010. Asset owners & maintenance. Program Office WCM, Breda, The Netherlands.

Veldman, J., Klingenberg, W. & Wortmann, J. C., 2011. Managing condition based maintenance technology: a multiple case study in the process industry. *Journal of Quality in Maintenance Engineering,* 17 (1), 40-62.

Veldman, J., Wortmann, J. C. & Klingenberg, W., 2010. Typology of condition based maintenance technology: a multiple case study in the process industry. *Journal of Quality in Maintenance Engineering,* in press.

Verbeek, M., 2000. *A Guide to Modern Econometrics*, Wiley.

Waeyenbergh, G. & Pintelon, L., 2002. A framework for maintenance concept development. *International Journal of Production Economics,* 77 (3), 299-313.

Waeyenbergh, G. & Pintelon, L., 2004. Maintenance concept development: a case study. *International Journal of Production Economics,* 89 (3), 395-405.

Waeyenbergh, G. & Pintelon, L., 2009. CIBOCOF: a framework for industrial maintenance concept development. *International Journal of Production Economics,* 121 (2), 633-640.

Wallace, T. F., 1984. IN Wallace, T. F. (Ed.) *APICS Dictionary.* Falls Church, American Production and Inventory Control Society.

Wang, F. & Hannafin, M. J., 2005. Design-based research and technology-enhanced learning environments. *Educational Technology Research and Development,* 53 (4), 5-23.

Wapakabulo, J., Dawson, R., Probets, S. & King, T., 2005. A step towards the adoption of data-exchange standards: a UK defence community case study. *The 4th Conference on Standardization and Innovation in Information Technology (SIIT 2005).* Geneva, Switzerland.

Wikipedia, ATA Spec 100: Manufacturers' Technical Data.

Wilkes, W., 2005. Networking among product ontologies: The standard ISO13584 - PLIB and related development. *PRODIS 2005, Workshop on product-related data in information systems in conjunction with Informatik 2005.* Bonn, Germany.

Wilson, P. F., Dell, L. D. & Anderson, G. F., 1993. *Root cause analysis: a tool for total quality management,* Wisconsin, ASQ.

Yin, R. K., 1994. *Case study research: design and methods*, Newbury park.