Continuous Improvements of Complex Technical Systems

Aspects of Stakeholder Requirements and System Functions

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ABSTRACT

In today’s society we are all strongly dependent on correct functions of technical systems. These systems tend to increase in both complexity and criticality, at the same time as they often have a rather long life. During this long life the stakeholders’ requirements on the functions of the systems change. In order to maintain a high level of stakeholder satisfaction organisations responsible for the system have to respond to the changes through system development and continuous improvements. When the technical system is both complex and critical it is even more important that the work with continuous improvements is done in a systemic and systematic way. This is because a modification may result in unwanted side effects and a small change in one part of the system may have a major negative impact on many other parts of the system, and also have far reaching decisive consequences.

The purpose of this thesis is to explore and describe how an organisation can work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements, in order to increase stakeholder satisfaction with a reduced amount of resources. To fulfil the stated purpose a case study supported by a literature study has been made. The case study focused on a modern combat aircraft, which is considered as a highly complex and safety critical system with stringent requirements on low life cycle cost.

The result of the study may be described in two parts. The first part is a theoretical management framework that combines aspects of Quality Management, Requirements Management, and Health Management. The framework describes on a conceptual level how the work with continuous improvements may be enhanced through synergism achieved by the combination. The second part, which is based on both theoretical and empirical findings, is a model intended to support the work with continuous improvements. The model includes a number of combined and adapted methodologies and tools that enable traceability between stakeholder requirements and the critical system functions that should be covered by tools that support Condition Monitoring, Diagnostics, and Prognostics.

Keywords: Quality Management, Requirements Management, Health Management, Continuous Improvements, Stakeholder Requirements, System View, Complex Critical Technical System, System Functions, Condition Monitoring, Diagnostics and Prognostics
I dagen samhälle är vi alla starkt beroende av korrekta funktioner hos tekniska system. Dessa system tenderar att bli både mer komplexa och kritiska, samtidigt som de har en lång livslängd. Under denna långa livslängd förändras intressenternas krav på systemets funktioner. För att bibehålla en hög grad av belåtenhet hos intressenterna måste de organisationer som är ansvariga för systemet svara mot förändringarna med systemutveckling och ständiga förbättringar. När det tekniska systemet är både komplext och kritiskt är det än viktigare att arbetet med ständiga förbättringar genomförs på ett systemiskt och systematiskt sätt. Detta beror på att en modifiering kan resultera i oönskade sidoeffekter samtidigt som en liten förändring i en del av systemet kan ha en stor negativ påverkan på många andra delar av systemet och även ha långt gående och avgörande konsekvenser.

Syftet med denna avhandling är att undersöka och beskriva hur en organisation kan arbeta med ständiga förbättringar av funktionerna hos komplexa tekniska system i en omgivning av föränderliga intressentkrav, för att öka belåtenheten hos intressenterna med minskade resurser. För att uppfylla syftet har en fallstudie, stödd av en litteraturstudie, genomförts. Fallstudien fokuserade på ett modernt stridsflygplan, som anses vara ett ytterst komplext och säkerhetskritiskt system med hårda krav på låga livscykelkostnader.


Sökord: offensiv kvalitetsutveckling, kravhantering, tillståndshantering, ständiga förbättringar, intressentkrav, systemsyn, komplexa kritiska tekniska system, systemfunktioner, tillståndövervakning, diagnostik och prognostik
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This thesis includes an extended summary and the following three papers, appended in full.


PART I: THE THEORETICAL FOUNDATION

CHAPTER 1: INTRODUCTION
In this first chapter of the thesis, a short description of the research area will be outlined. Thereafter the purpose of the study, the stated research questions, and the chosen limitations will be presented. Thereafter a summary of the introduction will be outlined and finally, the structure of the thesis will be described.

CHAPTER 2: THEORETICAL FRAME OF REFERENCE
In this chapter some theories with complementary perspectives upon continuous improvements of complex technical systems will be presented. Theories about Quality Management, Requirements Management, and Health Management will be outlined. Examples of some central definitions will also be presented. However, the author’s perspectives on the theories presented and the definitions selected in this thesis will be described in Chapter 3 (Perspectives on Presented Theories).

CHAPTER 3: PERSPECTIVES ON PRESENTED THEORIES
In this chapter the author’s perspectives on the presented theories will be outlined. A theoretical management framework based on the combination of Quality Management, Requirements Management, and Health Management will also be described. Further on, two theoretical propositions will be formulated. In addition, some chosen definitions vital for this study will be presented. Both the management framework and the propositions will be applied as support in the collection and analysis of empirical data.

CHAPTER 4: RESEARCH DESIGN
In this chapter some research options and performed choices will be discussed. Areas such as research purpose, perspective, and strategy will be presented and described. Aspects of data collection and analysis will also be briefly described. In addition to this, some aspects of reliability and validity will be discussed. Finally, a roadmap that summarises the performed choices will be presented.
1 INTRODUCTION

In this first chapter of the thesis, a short description of the research area will be outlined. Thereafter the purpose of the study, the stated research questions, and the chosen limitations will be presented. Thereafter a summary of the introduction will be outlined and finally, the structure of the thesis will be described.

1.1 Continuous Improvements of Complex Technical Systems

In today's society we are all strongly dependent on correct functions of technical systems, which have made us vulnerable to disturbances. Our vulnerability is exposed on occasions such as the mass power supply failure in North America that affected Toronto, Ottawa, New York, Detroit, Queensland, and the states of New Jersey and Connecticut (Canada and USA, August 14, 2003). Some other, well known, examples when technical systems have failed are the accident at a nuclear power plant at Three Mile Island (USA, March 28, 1979), the leak from a chemical plant at Bhopal (India, December 23, 1984), the explosion of the space shuttle Challenger (USA, January 28, 1986), the explosion of a nuclear reactor in Chernobyl (Russia, April 26, 1986), the Concorde crash outside Paris (France, July 25, 2000), and the explosion of the space shuttle Columbia (USA, February 1, 2003).

The technical systems that surround us, and that we are dependent on, tend to increase in complexity (Juran & Godfrey, 1999). These complex technical systems often have a rather long life (see, for example, White & Edwards, 1995; Sandberg & Strömberg, 1999) For example, a combat aircraft has a life of about 30 years (Sandberg & Strömberg, 1999). During this relatively long life, the requirements on the systems' functions will change due to the technical development, and changes in the needs of stakeholders, operational environment, laws and regulations (Bohner & Arnold, 1996; North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm & Schockert, 2003). Here a stakeholder is viewed as anyone who is affected by the system or by the process used to produce the system, today or in the future (see the combination of discussions in North et al., 1998; Juran & Godfrey, 1999; ISO/IEC 15288).

In order to maintain a high level of stakeholder satisfaction, throughout the system's whole life cycle, organisations responsible for the systems have to respond to changes in requirements through system evolution and continuous improvements (see North et al., 1998; Juran, 1992; Kotonya &
Sommerville, 1998; Herzwurm & Schockert, 2003). Many complex technical systems of today are also critical ones with stringent requirements on safety, reliability, availability, maintainability, and security, e.g. aircraft, nuclear power plants, and spacecraft. For many complex technical systems the requirements on lower cost of operation and support throughout the system’s life cycle have also grown in importance (Moubray, 1997; Sommerville & Sawyer, 1997; Cini & Griffith, 1999; Sandberg & Strömberg, 1999; Schmidt, 2001). The latter situation has led to the development of concepts such as Life-Cycle Cost, Life-Cycle Profit, and Life-Cycle Assessment (see, for example, Blanchard, 1992; Ciambrone, 1997; Ahlmann, 2002).

Both in theory and practice approaches that have been developed in order to manage the complexity and criticality of technical systems and their functions can be found (see, for example, Nowlan & Heap, 1978; Mobley, 1990; Stamatis, 1995; Moubray, 1997). At the same time one can find approaches that have been developed in order to manage changing stakeholder requirements (see, for example, Davis, 1993; Macaulay, 1996; Kotonya & Sommerville, 1998). In the stages of design and evolution of technical systems there is no clear border between stakeholder requirements and system functions. This is because the definition of a system is dependent upon how its boundaries are drawn (Hollnagel et al., 1995), which in turn will affect the perspective. Even though one perspective is often dominant, some approaches combine the two (see, for example, Akao, 1992). However, these approaches may, on the other hand, fail to deal with the evolutionary nature of complex systems (Herzwurm & Schockert, 2003). Therefore, the work with continuous improvements of complex technical systems can probably benefit from a combination of appropriate approaches with perspectives that emphasise requirements or functions.

Some examples of approaches that are used to maintain and improve technical systems are Quality Management, Requirements Management, and Health Management. The first approach, Quality Management, emphasises continuous improvements that are initiated by stakeholder requirements (which are expressed as needs, wants, desires, expectations, and perceived constraints), and supported by performed measurements (see, for example, Shewhart, 1931; Juran, 1992; Deming, 1993). Requirements Management is an approach that includes methodologies and tools for the management of dynamic stakeholder requirements throughout the technical system’s whole life cycle (see, for example, Davis & Leffingwell, 1996; Macaulay, 1996; Kotonya & Sommerville, 1998). The
third approach, Health Management, can be applied in order to improve the safety and reliability of technical systems, and also to decrease the combined cost of operation and support throughout the system's life, through the application of monitoring, diagnostic and prognostic technologies (see, for example, Mobley, 1990; Becker et al., 1998; Litt et al., 2000; Baroth et al., 2001; Campbell & Jardine, 2001; Dunne et al., 2001; Hess & Fila, 2002).

When the technical system is both complex and critical it is even more important that the organisational work with stakeholder focused continuous improvements is performed in a systemic and systematic way. This is because the impact of changes becomes more difficult to understand when the complexity of systems increases (Flood & Carson, 1993; Bohner & Arnold, 1996). A modification may result in unwanted side effects and a small change in one part of the system may have a major negative impact on many other parts of the system, and also have far reaching decisive consequences (Bohner & Arnold, 1996; Sommerville & Sawyer, 1997). When the system is critical these unwanted effects may result in human death or injury, damage to, or loss of, a technical system or property, or environmental damage (MIL-STD-882C; Sommerville & Sawyer, 1997). Therefore, it seems highly important for an organisation to establish and implement an approach that identifies and handles stakeholder requirements in a proper way, at the same time as the resulting changes of the technical system are performed and controlled in a systematic way. This systemic and systematic approach for stakeholder focused continuous improvements should enable both increased stakeholder satisfaction and a reduced amount of necessary resources.

In summary, existing theories related to the described area often focus on either requirements of stakeholders or functions of systems. When there exists a link between stakeholder requirements and system functions there is seldom any averseness to the evolutionary nature of complex systems with a long life. At the same time the practical work of changing stakeholder requirements and corresponding improvements of complex system functions may lead to major unwanted effects and far reaching negative consequences. Therefore, it is of both theoretical and practical interest to explore and describe the work with continuous improvements of complex technical systems.
1.2 **Purpose**
The purpose of this thesis is to explore and describe how an organisation can work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements, in order to increase stakeholder satisfaction with a reduced amount of resources.

1.3 **Research Questions**
In order to fulfil the stated purpose, two research questions are to be answered:

- What kinds of methodologies and tools can support the work with stakeholder focused continuous improvements of complex technical system functions?

- How can an organisation work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements?

1.4 **Limitations**
There are mainly two limitations made in this study.

Firstly, the research focuses on methodologies, and to some extent tools, that are appropriate to apply in order to find a correspondence between stakeholder requirements and critical functions of a complex technical system. The reason for this limitation is that the key to successful work with continuous improvements is thought to lie in the correspondence between stakeholder requirements and system functions, and the traceability between the two. The present writer thinks that this traceability is especially crucial when the system is a critical one, in which case these system functions should be covered by monitoring, diagnostic and prognostic capabilities. A consequence of this limitation is that values within studied approaches are not in direct focus, even though they probably influence the methodologies and tools that are applied within the different approaches.

As a second limitation, the purpose is not to explain patterns related to the studied phenomenon by included causal relationships and the meaning of these relationships. The causality is instead embedded in the fundamental theoretical assumptions of the study. The reason for the second limitation is that the explorative and descriptive nature of the purpose is believed to make both a theoretical and a practical contribution. The theoretical
contribution is aimed at clarification of an area that seems to be vaguely described in the scientific literature. The practical contribution is mainly directed towards organisations responsible for the design and evolution of complex technical systems, by providing a systemic and systematic approach to their work. This will hopefully also have important positive practical implications for other stakeholders of the system, through a reduced risk of unwanted effects and consequences.

1.5 Introduction Summary
In Figure 1.1 the introduction of this thesis is summarised. The summarisation also coincides with the order of the sections of this introductory chapter.

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**Figure 1.1** A summary of the thesis introductory chapter, illustrating the order and naming of included sections.

In the first section of this introductory chapter (*Continuous Improvements of Complex Technical Systems*) a short description of the research area have been described. Aspects of continuous improvements of complex and critical technical systems in the context of changing requirements of system stakeholders have been high lightened.

In the second section (*Purpose*) the purpose of the study has been presented, based on the description of the research area.

In order to fulfil the stated purpose two research questions that shall be answered have been stated in the third section (*Research Questions*).
The limitations of this study have been presented and motivated in the fourth section (Limitations) of this introductory chapter.

This fifth section includes a short summary and display of the thesis first chapter (Introduction Summary).

The sixth and last section of this chapter (Thesis Structure), will present the structure of the whole thesis, and shortly present the content of each chapter and the three papers that are appended.

1.6 Thesis Structure
The structure of this thesis is illustrated in Figure 1.2.

In the first chapter (Introduction) of this thesis a short description of the research area is outlined. Thereafter the purpose of the study, the stated research questions, and the chosen limitations are presented. Finally, the structure of the thesis is described.

In the second chapter (Theoretical Frame of Reference) the theories that have been studied will be presented. Theories about Quality Management, Requirements Management, and Health Management will be outlined. Examples of some central definitions will also be presented.

In Chapter 3 (Perspectives on Presented Theories) the author's perspectives on the presented theories will be outlined. A theoretical management framework based on the combination of Quality Management, Requirements Management, and Health Management will also be described. Furthermore, two theoretical propositions will be formulated. In addition, some chosen definitions vital for this study will be presented. Both the management framework and the propositions will be applied as support in the collection and analysis of empirical data.

In the fourth chapter (Research Design) some research options and performed choices will be discussed. Areas such as research purpose, perspective, and strategy will be presented and discussed. Aspects of data collection and analysis will also be briefly described. In addition to this, some aspects of reliability and validity will be discussed. Finally, a roadmap that summarises the performed choices will be presented.

In the fifth chapter (Research Project and Research Process) the background to the research project and the phases of the research process will be described.
Figure 1.2 The structure of the thesis, illustrating included chapters, their name and content. The kind of papers that are appended is also displayed.
Chapter 6 (Case Description) will start with a short presentation of some general background information about the studied case. After that, the case will be described in accordance with the theoretical framework of the study, with special focus on methodologies and tools for Requirements Management and Health Management.

In the seventh chapter (Analysis and Results) the combined analysis of the theoretical and empirical findings will be presented. The results of this analysis will also be outlined.

The discussion in the concluding chapter (Conclusions and Discussion) will summarise some major conclusions that may be drawn from this study. The areas of discussion will be centred on the stated research purpose and research questions of the study. Finally, some aspects of reliability, validity, and further research will be discussed.

There are also three papers appended to the thesis. These papers are one conference paper, one journal paper, and one research report. The conference paper explores and describes Health Management from a Quality Management perspective and points to Requirements Management as a complementary management approach to the other two. The second paper, which is a journal paper, explores and describes a theoretical management framework, consisting of Quality Management, Requirements Management, and Health Management. The framework describes on a conceptual level how an organisation can enhance its work with continuous improvements by synergism achieved by the combination of the three management approaches. The third paper is a research report that describes a model that is intended to support the work with continuous improvements of complex technical systems. The model includes a number of combined and adapted methodologies and tools that enable traceability between stakeholder requirements and the critical system functions that should be covered by tools that support Condition Monitoring, Diagnostics, and Prognostics.
2 THEORETICAL FRAME OF REFERENCE

In this chapter some theories with complementary perspectives upon continuous improvements of complex technical systems will be presented. Theories about Quality Management, Requirements Management, and Health Management will be outlined. Examples of some central definitions will also be presented. However, the author’s perspectives on the theories presented and the definitions selected in this thesis will be described in Chapter 3 (Perspectives on Presented Theories).

2.1 Quality Management

Some key-phrases about quality in the literature are “Quality means conformance to requirements” (Philip B. Crosby), “Quality is fitness for use” (Joseph M. Juran), “Quality should be aimed at the needs of the customer, present and future” (W. Edwards Deming), “the lack of quality is the losses a product imparts to society from the time the product is shipped” (Genichi Taguchi). In the above definitions of quality the focus on customers and their needs is obvious. Deming has expanded the customer focus to include also future customers as well, and Taguchi stresses that the losses for the whole of society after delivery of the product should be considered, a view which is related to today’s concept of sustainable development, as described by, for instance WCED (1987).

Garvin (1988) classifies five different approaches to defining quality. These are transcendent, product-based, user-based, manufacturing-based, and value-based quality. According to the transcendent approach quality cannot be defined precisely, it is a simple unanalysable property that can only be learned to be recognised through experience. Product-based definitions view quality as a precise and measurable variable, where a higher quality can only be obtained at a higher cost. User-based definitions are founded on the premise that quality lies in the eyes of the beholder, and that the product that best satisfies the consumer preferences is of the highest quality. Manufacturing-based definitions are concerned with engineering and manufacturing practices, which means that any deviation from a design or specification implies a reduction in quality. Value-based definitions, finally, define quality in terms of cost and price; therefore quality is seen here as performance or conformance at an acceptable price or cost.

Garvin (1988) discusses drawbacks to each approach to quality and concludes that it is beneficial to adapt multiple approaches, which means
that it necessary to actively shift approaches when the product moves from design to market. Initially it may be favourable to have a user-based approach, and identify the requirements that the market has. At the design stage a product-based approach may be used in order to deploy desired characteristics into specifications. During manufacturing a manufacturing-based approach can help to ensure that the manufactured product meets the specifications. Garvin points out that it is beneficial to be aware of different approaches to quality, even though specific approaches are probably in focus in different phases of the development of a product, or for different departments in a company.

The evolution of Quality Management may be described in different ways. One common description is made up of four stages that follow each other. These stages are Quality Inspection, Quality Control, Quality Assurance, and Total Quality Management (see, for example, Garvin, 1988; Dale, 1999).

At the first stage, Quality Inspection, the focus was on inspection of some critical characteristics of finished products relative to stated requirements. The inspections of products were performed by an inspection department. At the second stage, Quality Control, characteristics of the production process were inspected at some appropriate time interval, and compared to the inherent variation of the process. At this second stage the responsibility for quality was mainly located in the manufacturing and engineering departments. Quality Assurance is the third stage and here the whole production chain, from design to market, and the contribution of all functional departments is considered, in order to prevent failures. This area is closely connected to issues related to routines, responsibilities, and organisation established in standards such as QS9000 and ISO9000. However, top management is only involved to a limited degree. Finally, at the fourth stage, Total Quality Management, everyone in the organisation is considered responsible for quality and top management exercises strong and committed leadership. Total Quality Management further widens the focus and emphasises the market and customer needs. (See Garvin, 1988 and Dale, 1999)

Kroslid (1999) describes another evolution of Quality Management. In this description there are two different schools of Quality Management. One is the Deterministic School of Thoughts and the other is the Continuous Improvement School of Thoughts. These two schools form a dual path of the evolution of Quality Management, in contrast to the single evolutionary path described by, for instance, Garvin (1988) and Dale (1999).
The Deterministic School of Thoughts may be seen as related to Quality Inspection and Quality Assurance. This part of Quality Management started with Frederick W. Taylor in the end of the 19th century (see Taylor, 1911). Taylor’s ideas were followed by British and American military standards, which later became the base for ISO9000. The Continuous Improvement School of Thoughts, which focuses on variation and improvements, may be seen as related to Quality Control and Total Quality Management. This part of Quality Management can be traced back to Walter A. Shewhart in the 1930s (see Shewhart, 1931, 1939). (Kroslid, 1999)

The view and naming of Quality Management also differ between different descriptions, which can probably be explained by the different stages or schools of Quality Management, as described above. However, some authors have suggested a system approach to the concept (see e.g. Shiba et al., 1993; Dean & Bowen, 1994; Hellsten & Klefsjö, 2000). According to Hellsten & Klefsjö (2000), Quality Management may be seen as a management system that aims at increased external and internal customer satisfaction with a reduced amount of recourses. This management system consists of the three interdependent elements: values, methodologies, and tools, see Figure 2.1. A similar view of Dependability Management has been presented by Akersten & Klefsjö (2003).

That the core values are fundamental to Quality Management is commonly stressed (see e.g. Kanji & Asher, 1993; Oakland, 1993; Lewis, 1996; Boaden, 1997). According to Hellsten & Klefsjö (2000) the core values constitute a very important element as they are the basis of the culture of the organisation and also the basis of goals set by the organisation. However, the naming, formulation, and number of values differ somewhat between different authors. In the Malcolm Baldrige National Quality Award “11 core values and concepts” may be found (NIST, 2002), while Dale (1999) discusses “eight key elements”, and ISO9000 includes “eight management principles”. In all the sources described above, and in Figure 2.2, values that may be summarised as those mentioned in Figure 2.1 may be found. Since these values are frequently mentioned in the literature describing Quality Management they may be seen as core values of Quality Management (Hellsten, 1997).
Figure 2.1 Quality Management, named Total Quality Management and seen as a continuously evolving management system consisting of core values, methodologies and tools. It is important to note that the methodologies and tools in the figure are just examples and not a complete list. In the same way the core values may also vary a little between different organisations and over time. From Hellsten & Klefsjö (2000, p. 241).

Another element of the management system is the set of methodologies, which are ways of working in the organisation to reach the goals. A few examples of methodologies are Quality Function Deployment (QFD), Design of Experiments (DoE), Failure Mode & Effect Analysis (FMEA), Self-Assessment, and Risk Analysis. The third element in the management system consists of tools that are rather concrete and well-defined. Sometimes these tools have a statistical basis, to support decision-making or facilitate the analysis of data. Some tools that support the methodologies mentioned above are the House of Quality (HoQ), factorial design sheets, FMEA-sheets, the booklet of criteria to the Malcolm Baldrige National Quality Award, and Fault Trees. (Hellsten & Klefsjö, 2000; Akersten & Klefsjö, 2003)
Figure 2.2 The core values which are said to be the basis for the ISO9000:2000 (ISO, 2002), The European Quality Award (EFQM, 2002), and the Malcolm Baldridge National Quality Award (NIST, 2002).

2.1.1 Systems and System View

One of the core values of Quality Management may be formulated as System View, see Figure 2.2. However, there are a lot of different views and definitions of what a system is. According to ISO/IEC 15288 a system may be viewed as “a combination of interacting elements organised to achieve one or more stated purposes”. Deming (1993) states that “a system is a network of interdependent components that work together to try to accomplish the aim of the system”. Another definition is that “a system is a deterministic entity comprising an interacting collection of discrete elements” (NUREG-0492).

The definitions above have all roughly the same meaning. There are a number of elements that interact to achieve an aim. The interaction between the elements ensures that the system is something more than the sum of the individual elements, and the interaction between the elements also means that if any element changes in some way, e.g. due to failure or modification, the system will also change (NUREG-0492). In this view the complexity of a system may be measured in terms of the number of elements, and the number and attributes of the relationships between elements (Flood & Carson, 1993). This means that the complexity of a system increases with
the number of elements, the number of relationships between the elements, and the attributes of the relationships.

Senge (1990) presents system thinking as a discipline for seeing wholes. The system thinking provides a framework for seeing interrelationships and patterns of change instead of static snapshots. Senge (1990) argues that system thinking is a set of general principles that have been distilled during the twentieth century, spanning fields such as social sciences, engineering, and management. System thinking is also presented by Senge (1990) as a specific set of methodologies and tools.

To understand a complex system it is necessary to use abstraction and decomposition (Törne, 1996). Abstraction means that information not needed for the understanding of a specific feature is concealed, or that details in the whole design are concealed in order to enable a focus on a specific element, or a combination of these two (Törne, 1996). Decomposition means that the system is divided into elements small enough to understand the function of these elements (Törne, 1996; Tossavainen, 2002). However, one cannot necessarily understand the function of the whole system by a study of the system elements alone (Deming, 1993; Tossavainen, 2002). One has also to understand the relationships between the elements (Deming, 1993; Törne, 1996). It is also necessary to identify the studied system’s relationship to other neighbouring and superior systems (MIL-STD-1629A; Deming, 1993; Stamatis, 1995). Interfaces within and between systems are thus crucial in the study of systems (MIL-STD-1629A; Stamatis, 1995).

Hollnagel et al. (1995) state that a system can be completely understood due to two situations. Either because the system’s performance is stable and remains within a limited number of possible states, although the system itself may be complex, or because it is so simple that all its possible states can be analysed or anticipated (Hollnagel et al., 1995).

Most of the time a system is functioning as expected, because it was designed and built that way, which may misleadingly be thought as a complete understanding of the system. However, at the moment when something goes wrong, and in complex system this seems to be inevitable, the brittleness of the understanding becomes clear. (Hollnagel et al., 1995)

**Non-Technical Systems**

Two examples of how the system view can be applied, also illustrating the benefits of this perspective are described by Hellsten & Klefsjö (2000) and
Akersten & Klefsjö (2003), as referred to in the previous section. They used the system view in order to structure a management approach. Deming (1993) applies the system view in order to describe the management of an organisation, and makes comparisons to other systems such as simple technical systems, specific industries, and whole countries.

Checkland (1999) describes human activity systems. Such a system is a notational purposive system, which expresses some purposeful human activity. The system is notational since it is not a description of real-world activities, but an intellectual construct. One part of the system thinking is to draw out different perspectives of the problem situation and structure it.

One example of a simple human activity system is described by Juran (1992). This system consists of the three interdependent elements supplier, processor, and customer. The supplier provides something to its customer. The supplier’s customer, called the processor, processes this input to some output, which in turn is delivered to the processor’s customer. Therefore each processor is also a customer and a supplier. In addition to this, each processor can have multiple suppliers and customers. It is fairly obvious that even this rather limited stakeholder system, with only three roles, in reality may become rather complex.

**Technical Systems**

Hubka (1982, p. 111) defines a technical system as “a general category of artificial deterministic systems that performs the necessary effects to achieve the transformation of operands”. Technical system is a collective term for machines, devices, apparatus, equipment, and plants (Hubka, 1982). Hollnagel et al. (1995) state that the technical part of a system not necessarily should be considered as a single physical machine, such as a lathe or a pump. Instead, a technical part of a system possibly includes a large number of components, machines, computers, controlling devices, and so forth (Hollnagel et al., 1995). Some examples of complex technical systems are aircraft, nuclear power plants, and computer networks (Hollnagel et al., 1995).

Complex technical systems often have a rather long life (see, for example, White & Edwards, 1995; Sandberg & Strömberg, 1999). As one example a combat aircraft typically has a life of about 30 years (see Sandberg & Strömberg, 1999). The requirements on these systems change over the life span due to the technological development, and changes in the needs of stakeholders, operational environment, laws and regulations (see North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm &
In order to maintain a high level of stakeholder satisfaction throughout the whole life cycle of the system, it has to be continuously improved (see Kotonya & Somerville, 1998; Herzwurm & Schockert, 2003).

Many complex technical systems of today are also critical ones, with stringent requirements on reliability, availability, maintainability, security or safety (Sommerville & Sawyer, 1997), e.g. aircraft, nuclear power plants, and spacecraft. The requirements on lower cost of operation and support throughout the system’s life cycle have increased in many complex technical systems (see, for example, Moubray, 1997; Cini & Griffith, 1999; Sandberg & Strömberg, 1999; Schmidt, 2001).

**Joint Systems**

Hollnagel et al. (1995, p. 1) define a joint system as “the unique combination of people and machines that is needed to carry out a given task or provide a specific function.” Hence the joint system may be seen as a combination of a non-technical system, as described by Juran (1992), and a technical system, as described by Hubka (1982).

Sharp et al. (1999) have the same basic description of a stakeholder system as Juran (1992), but add satellite stakeholders and a technical system. The satellite stakeholders interact with the processor in a variety of ways, e.g. by communication, the reading of a set of rules or guidelines, and searching for information. The addition of satellite stakeholders, made by Sharp et al. (1999), contributes further to the complexity of the human activity system described by Juran (1992). However, the addition of a technical system transforms the stakeholder system into a joint system, according to the definition given by Hollnagel et al. (1995, p.1).

Blanchard (2001) states that a system is a construct or collection of different elements, which together produce results that not are obtainable by the elements alone. Blanchard (2001) further states that the elements of the system may include people, hardware, software, facilities, policies, and documents. These elements are required to produce system-level results. The results of the system include such things as properties, characteristics, functions, behaviour, and performance that emerge on a system level. The value added by the system as a whole is beyond that contributed independently by the parts. The value is primarily created by the relationship among the parts, their interconnection.
Hollnagel et al. (1995) point out that the boundaries of the joint system are set according to the nature of the investigation, and the level of analysis. In some cases the boundary will coincide with the physical space of the control room. However, it is frequently necessary to include elements that are distributed in both time and space, such as management, training, safety polices, software design, and so forth (Hollnagel et al., 1995).

### 2.1.2 The Failure Concept

There are many different definitions of failure. One extensive survey of literature related to information system failure has been presented by Lyytinen & Hirschheim (1987). They state that the failure of a system is something that poses a problem for someone or some group, i.e. the stakeholders of the system. The failure thus signifies a gap between some existing situation and a desired situation for the members of a particular stakeholder group. A system failure may thus be defined as the inability of the system to meet a specific stakeholder group’s expectations. This failure concept is in line with the one given by Nowlan & Heap (1978, p. 18) where “a failure is an unsatisfactory condition” that is related to the design requirements, but also to user requirements, and the consequences of failure in the particular operating context. A further discussion about the failure of system functions may be found in Section 2.3 (Health Management).

The definition of failure described by Lyytinen & Hirschheim (1987) and Nowlan & Heap (1978) may be related to the gap model presented by Zeithaml et al. (1990). Even though the gap model has been developed with services in mind, the fundamental ideas behind the model may be applicable to all kinds of products, where a product includes services, goods, or a combination of the two (Bergman & Klefsjö, 2003).

According to Zeithaml et al. (1990) there are four gaps that may explain why customers get disappointed with something that an organisation delivers. The first gap depends on the inability of the delivering organisation to understand the expectations of the customers. There may also be a gap between the organisational understanding of customers’ expectations and the specification of what the organisation is to produce. The third gap is between the design specification and what is actually delivered to the customers. The fourth and last gap is between what is delivered by the organisation and what has been promised to the customer. In order to achieve customer satisfaction all four gaps have to be closed.
The relationship between customer and stakeholder will be further discussed in Chapter 3 (Perspectives on Presented Theories).

2.2 Requirements Management

There are different definitions of requirements. According to ISO/IEC 15288 “stakeholder requirements are expressed in terms of the needs, wants, desires, expectations and perceived constraints of identified stakeholders”. Here, stakeholder requirements include, but are not limited to, the needs and requirements imposed by society, the constraints imposed by an acquiring organisation and the capabilities and limiting characteristics of operator staff. Davis (1993) defines a requirement as “a user need or necessary feature, function, or attribute of a system that can be sensed from a position external to that system”. According to IEEE STD 610.12 a requirement is defined as:

- A condition or capability needed by a user to solve a problem or achieve an objective.
- A condition or capability that must be met or possessed by a system or system element to satisfy a contract, standard, specification, or other formally imposed documents.
- A documented representation of a condition or capability as in one of the two former statements.

There are different ways of classifying requirements. One traditional way is to classify the requirements as functional or non-functional (Mylopoulos et al., 1999).

Functional requirements may be defined as what the system does, i.e. describing a specific function. Non-functional requirements may be defined as how the system works in relation to the organisation, or as constraints on the functional requirements. Non-functional requirements are global quality attributes of a system, such as safety, reliability or availability. (Grimshaw & Draper, 2001)

Requirements Management may be considered as an approach that has been developed within the computer industry and science, in response to increasing demands and costly failures (see, for example, Davis, 1993; Alexander, 1997). The trends that have had a powerful impact on the development of Requirements Management may be summarised as follows (Alexander, 1997):

- Falling prices and increasing accessibility of computer-based systems.
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- Growing interactivity, bringing a widening range of users with rising expectations.
- Increasing memory and program size, bringing problems of complexity.
- Rising size and cost of system failures despite ever-better development tools.

According to Davis & Leffingwell (1996), Requirements Management is a systematic approach to eliciting, organising, documenting, and managing both the initial and the changing requirements of a technical system. A principal result of this work is the development of one or more requirement specifications, which define and document the complete external behaviour of the system to be constructed. Davis & Leffingwell (1996) consider Requirements Management as partly a management process and partly an engineering discipline, and states that it therefore can be used effectively to manage both technical complexity and requirements on the system.

Kotonya & Sommerville (1998) describe Requirements Management as the managing of changes in the requirements, and the relationship between requirements on a system. Requirements Management checks that it is technically and economically possible to perform the proposed changes. If the change applies to a specific requirement it is important to check what other requirements may be affected in some way. This requires that links between requirements, the sources of requirements and the system design must be recorded, i.e. traceability information.

The concept of traceability points to one characteristic of a good requirement. There are also a number of other characteristics that may be found in the literature. Typical characteristics of good requirements are that they should be correct, unambiguous, complete, consistent, ranked for importance and/or stability, modifiable, and traceable (ANSI/IEEE STD 830, pp. 11-13; IEEE STD 830, pp. 4-8). See also Table 2.1.

Requirements Management includes methodologies and tools for establishing and executing a formal procedure for collecting, verifying, considering, and studying how changes of requirements affect the system (Kotonya & Sommerville, 1998). Requirements Management may thus be seen as a way to managing mainly four activities by the feedback from these activities (Bohner & Arnold, 1996). The first step is to study the proposed new requirements, or modifications of existing requirements, and make decisions about necessary changes and appropriate actions, based on wanted and unwanted effects of the proposal. After that, the changes must be specified and designed. The changes must then be executed on the bases
of the specification, e.g. through document changes. Finally, the performed changes must be studied to see if they meet the new requirements, and if the system meets the other existing requirements.

Table 2.1 Characteristics of and descriptions of good requirements. After ANSI/IEEE STD 830 (pp.11-13) and IEEE STD 830 ( pp. 4-8).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>The requirement shall state something that the system shall meet.</td>
</tr>
<tr>
<td>Unambiguous</td>
<td>The requirement shall have only one interpretation. As a minimum, this requires that each characteristic of the final system be described using a single unique term.</td>
</tr>
<tr>
<td>Complete</td>
<td>The requirement shall be both determined and significant.</td>
</tr>
<tr>
<td>Consistent</td>
<td>The requirement shall not conflict with other requirements.</td>
</tr>
<tr>
<td>Ranked for Importance and/or Stability</td>
<td>The requirement shall be ranked for importance and/or stability if it has an identifier to indicate its importance or stability.</td>
</tr>
<tr>
<td>Verifiable</td>
<td>The requirement shall have some cost-effective methodology with which a human or machine can check that the system meets the requirement.</td>
</tr>
<tr>
<td>Modifiable</td>
<td>The requirement shall be possible to change easily, completely, and consistently without affecting the structure and style of the requirement specification.</td>
</tr>
<tr>
<td>Traceable</td>
<td>The requirement shall have a clear development from its origin to its furthest development.</td>
</tr>
</tbody>
</table>

One major difference between the views on Requirements Management that may be seen in the descriptions by Davis & Leffingwell (1996) and Kotonya & Sommerville (1998) is that the former include both original (initial), or “first time”, requirements and later changes of these requirements, while the latter focus on changes of requirements that have been analysed earlier. The initial work with requirements is called Requirements Engineering by Kotonya & Sommerville (1998). It should be noted that the distinction between Requirements Engineering and Requirements Management is quite common in the literature, at the same time as both the meaning and the naming may differ between different descriptions. As a further example of this, Bohner & Arnold (1996) call the approach that they describe Change Impact Analysis. However, one universal component in different descriptions of Requirements Management is the requirements of some stakeholders on the system.
2.3 Health Management

The health, or condition, of a technical system changes over time, since the elements within the system are subjected to degradation, which sooner or later will lead to failure of the system. These effects may be due to ageing, design configuration, environment, or abuse of the system. According to Nowlan & Heap (1978, p. 18) "a failure is an unsatisfactory condition". This unsatisfactory condition is related to the design requirements, but also to user requirements, and the consequences of failure in the particular operating context. Further on, Nowlan & Heap (1978, pp. 18-19) define two different types of failures:

- A functional failure is the inability of an item (or the equipment containing it) to meet a specified performance standard.
- A potential failure is an identifiable physical condition which indicates a functional failure is imminent.

The reason for the classification of failures into potential and functional ones is that an unsatisfactory condition can either be a real inability to perform a necessary function, or a judgment, based on physical evidence, that it will soon be unable to perform such a function. A functional failure is the inability of a system to meet a specified performance standard. This includes a total inability of the system to perform a specific function, as well as a situation where the system performs the function at a lower level than required. A potential failure is an identifiable physical condition which indicates that a function failure is imminent. A potential failure is thus one which is related to the fact that the system will, within a short period of time, develop a functional failure. (Nowlan & Heap, 1978)

The evolution of Health Management may be viewed in the light of some trends seen in the description by Moubray (1997) about technical systems and their maintenance:

- Growing dependence on technical systems that become more complex, and that makes availability and reliability aspects more important.
- Growing awareness of safety and environmental issues due to the negative impact that an increased number of failures of technical systems have on these issues.
- Increasing focus on operation and support costs of technical systems, since these costs increase over time.
- Changes within maintenance from corrective actions, via preventive actions towards predictive actions.
One approach, intended to meet the increasing demands on technical systems was Reliability-Centred Maintenance, RCM (Nowlan & Heap, 1978). One vital contribution of RCM is the definition of potential failure, which led to the concept of Condition Based Maintenance (CBM) being accepted as one of the best ways of preventing functional failure (Coetzee, 1997).

In order to enable CBM, the health of the system must be monitored by Condition Monitoring (CM) of some critical functions of the system (Mobley, 1990; Martin, 1993; Campbell & Jardine, 2001). The CM results in collected data that represent the system’s health in some way (Mobley, 1990; Martin, 1993; Campbell & Jardine, 2001). The focus on CBM thus led to a completely new industry, providing tools for the monitoring of system health, being developed (Coetzee, 1997). Diagnostics is concerned with the interpretation of collected health data and the conclusion drawn about the system’s current health (Martin, 1993). On the basis of the diagnostic information decisions about condition based maintenance can be made (Mobley, 1990; Campbell & Jardine, 2001; Litt et al., 2000; Hess & Fila, 2002). An extension of diagnostics is prognostics, which tries to predict the future health of a technical system (Mobley, 1990; Becker et al., 1998; Martorell et al., 1999).

The aim of prognostics is to stop critical functional failures before they occur (see, for example, Mobley, 1990; Becker et al., 1998; Roemer et al., 2001). The prognostic information enables decisions about recommended maintenance that is not required for the moment, but advantageous to perform with currently required maintenance (Mobley, 1990; Litt et al., 2000; Hess & Fila, 2002). On the basis of the diagnostic information it is possible to determine if the operation should be terminated, or if it is possible to continue operation, with or without any restrictions (see, for example, Nowlan & Heap, 1978). Decisions about operation can be based on the prognostic information, in the same way as the diagnostic information, with the advantage of a planning horizon (see Mobley, 1990; Hess & Fila, 2002). Prognostics thus also enables a control of the aging of technical systems, which may be required by regulatory authorities, e.g. for nuclear power plants (Martorell et al., 1999).

The evaluation of performance and safety levels of a system can be based on selected indicators covering areas such as reliability, availability, maintainability, and safety. Condition Monitoring can support the planning of maintenance actions. Indicators in such an application must provide
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information about aging and degradation of the system. Condition Monitoring can then support the prognostication of the residual life of important elements within the system. (Martorell et al., 1999)

There are two main categories of indicators. The first category is basic or direct indicators, which are linked directly with the collected operational data, such as number of maintenance actions, type of maintenance actions, and cost of maintenance actions. The second category is indirect indicators, which are derived from direct indicators, e.g. reliability and availability. The indicators should also be established on the three levels component, subsystem, and system level. (Martorell et al., 1999)

As with most of the other approaches and concepts in this thesis, there is not one single definition or naming of Health Management. A lot of different descriptions and naming may be found in the literature. Mobley (1990) discusses Predictive Maintenance and Campbell & Jardine (2001) discuss Maintenance Excellence. Another approach that is similar to Health Management is Prognostics & Health Management (PHM), which is connected to the Joint Strike Fighter (JSF) developed in the USA (see, for example, Malley, 2001). A future concept, where the technical system is intended to perform autonomous maintenance, is Integrated Vehicle Health Management (IVHM), conceptualised at NASA (see, for example, Baroth et al., 2001). However, different descriptions of Health Management derive their origin from the thoughts of functional and potential failures as described by Nowlan & Heap (1978). This means that the lowest common denominator in different descriptions is system functions, which is interpreted and monitored in relation to some identified requirements.

Moubray (1997, p. 22) states that “a function statement should consist of a verb, an object and a desired standard of performance”. According to Stamatis (1995) a function is the task that the system (design, process, component, subsystem, or service) must perform, and this function must be communicated in a way that is concise, exact, and easy to understand. Stamatis (1995) further recommends that an active verb is applied in order to describe the function, since the active verb defines performance, and performance is what a function is. Nowlan & Heap (1978, p. 458) define a function as “the normal or characteristic actions of an item, sometimes defined in terms of performance capabilities”.

- 25 -
Nowlan & Heap (1978, pp. 19-20) state that the ability to identify either a functional failure or a potential failure depends upon three factors:

- A clear definition of the functions of an item as they relate to the equipment or operating context in which the item is to be used.
- A clear definition of the conditions that constitute a functional failure in each case.
- A clear definition of the conditions that indicate the imminence of this failure.
3 PERSPECTIVES ON PRESENTED THEORIES

In this chapter the author’s perspectives on the presented theories will be outlined. A theoretical management framework based on the combination of Quality Management, Requirements Management, and Health Management will also be described. Further on, two theoretical propositions will be formulated. In addition, some chosen definitions vital for this study will be presented. Both the management framework and the propositions will be applied as support in the collection and analysis of empirical data.

3.1 Perspective on Quality Management

The view on Quality Management used in this thesis may be seen as belonging to the Continuous School of Thoughts, as described by Kroslid (1998). The view may also be seen as originating in Quality Control and Total Quality Management, as described by Garvin (1993) and Dale (1999). The main reason for this statement is the focus on continuous improvements in this thesis.

A system approach to Quality Management is adapted, in line with the descriptions made by Shiba et al. (1993), Dean & Bowen (1994), and Hellsten & Klefsjö (2000). More specifically the system approach presented by Hellsten & Klefsjö (2000) is applied, where a system is defined as (Deming, 1993, p. 50):

A system is a network of interdependent components that work together to try to accomplish the aim of the system.

However, the author thinks that it may be valuable to modify the description made by Hellsten & Klefsjö (2000) a little, in order to emphasise the importance of requirements and support between the elements of the management system. This is done by redrawing Figure 2.1, as in Figure 3.1.

Another modification is to replace the word “customer” with “stakeholder”, in order, hopefully, to increase the transparency and inter-subjectivity to other management areas. The rationale for this choice is that the expanded customer view that often exists within Quality Management (as illustrated by, for example, North et al., 1998; Juran & Godfrey, 1999), is not necessarily applied within other management approaches. That the customer focus should include internal as well as external customers is commonly stressed in the quality literature (see, for example, Deming, 1993;
According to North et al. (1998) the external customers also include the community, the general public, and the shareholders. This expanded view of customers is in line with the one given by Juran & Godfrey (1999, p. 2.3), where customers are seen as “anyone who is affected by the product or by the process used to produce the product”. The expanded view of customers, outlined above, may implicate that it is more appropriate to talk about “stakeholders” instead of “customers”. Therefore, “customer” is, by the author of this thesis, seen as one category within the larger domain of “stakeholder” in the remaining part of this thesis. The definition of stakeholder applied in this thesis is:

A stakeholder is anyone who is affected by the product or by the process used to produce the product, today or in the future.

Figure 3.1 Quality Management as a management system that consists of core values, methodologies, and tools that are related to each other by requirements and given support. The aim is to achieve increased stakeholder satisfaction with a reduced amount of resources. From Söderholm (2003a), originally inspired by Hellsten & Klefsjö (2000) and Akersten & Klefsjö (2003).

Quality Management is seen as a system consisting of the three interdependent elements values, methodologies and tools that work together to try to accomplish the aim of the system. The aim of the system is increased stakeholder satisfaction with a reduced amount of resources.
(Hellsten & Klefsjö, 2000). The reason for the choice of a system view of Quality Management is that it is seen as the latest step in the evolution of the approach. At the same time the system view is believed to enhance the understanding of the approach, provide a means of structuring different aspects within the approach, and also enable a practical means of communication. A further discussion about the system view can be found in Section 4.2 (Research Approach).

In line with Kanji & Asher (1993), Oakland (1993), Lewis (1996), Boaden (1997), and Hellsten & Klefsjö (2000) the present writer regards the core values as fundamental to Quality Management. In this study four core values are believed to be most important to focus on. These core values may be formulated as Continuous Improvements, Stakeholder Focus, Fact Based Decisions, and System View. The other core values are not seen as unimportant, on the contrary they are seen as most important for the work with continuous improvements, but they are not directly focused on in this study.

Both the management system view of Quality Management and the four core values that are focused on may be seen as influencing the stated purpose and research questions, even if the core values are not explicitly articulated. This study is thus founded on the view of Quality Management as described above.

3.2 Perspective on Requirements Management

In order to implement the core value Stakeholder Focus within an organisation and be able to harvest its potential benefits, it is necessary to select appropriate methodologies and tools that can handle the complexity and dynamic nature of the stakeholder system. The present writer believes that these supporting methodologies and tools may be found in the area of Requirements Management.

The chosen perspective on Requirements Management is founded on the author's perspective on Quality Management, influenced by continuous improvements. This is illustrated in Figure 3.2.

Requirements Management is seen as an approach that consists mainly of four phases, see Figure 3.2. The first phase is to study the proposed new requirements, or modifications of existing requirements, and make decisions about necessary changes and appropriate actions, based on wanted and unwanted effects of the proposal. In the second phase the changes are specified and designed. Then, in the third phase, the changes
are executed on the basis of the specification. Finally, the performed changes are studied to see if they meet the new, or modification of existing, requirements, and if the system meets the other existing requirements. Vertical arrows illustrate support, while horizontal arrows illustrate the sequential work order, where previous activities lend support to the following ones.

![ Requirements Management Diagram](image)

**Figure 3.2** Requirements Management supported by four interrelated activities. Vertical arrows illustrate support, while horizontal arrows illustrate the sequential work order, where previous activities lend support to the following ones. From Söderholm (2003) and originally inspired by Bohner & Arnold (1996).

In this thesis Requirements Management is seen as the work related to both initial requirements and changes of these requirements, in line with the definition given by Davis & Leffingwell (1996). Requirements Management is thus not seen as only related to the management of changing requirements as described by Kotonya & Sommerville (1998). This choice is founded on the belief that methodologies and tools for the work with requirements are seen as very closely connected to each other, and also due to the iterative nature of the work with requirements. At the same time an initial requirement may be seen as a change from the state of no requirement at all. A requirement is defined in this thesis as:

*A requirement is expressed in terms of the needs, wants, desires, expectations, and perceived constraints of system stakeholders.*

### 3.3 Perspective on Health Management

In order to meet the increasing demands on lower operation and support cost many complex technical systems are designed for Health Management. This design also gives a potential for improving issues such as reliability and safety, which are important when the system is a critical one. However, the author of this thesis believes that methodologies and tools within Health Management can also support a realization of the core value Continuous Improvements, in particular when the technical system is complex and critical.
The view of Health Management in this thesis is illustrated in Figure 3.3, where horizontal arrows illustrate the path of health data and information, and vertical arrows illustrate given support. As a summary, health data is necessary for making diagnoses and prognoses of a technical system’s current and future health. On the basis of diagnostic and prognostic information it is then possible to make decisions about appropriate operation and support actions, both current and future. Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support may be seen as three interdependent methodologies. Appropriate tools should in turn support these methodologies.

Figure 3.3 Health Management supported by the three methodologies Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support. These methodologies are in turn supported by different tools, of which a few examples may be found in the figure. Vertical arrows illustrate given support, while horizontal arrows illustrate the path of health data and information. From Söderholm (2003a) and originally inspired by Söderholm & Akersten (2002).

3.4 Management Framework

By a combination of the three management areas described earlier in the previous chapter (Theoretical Framework) a theoretical Quality Management framework supported by Requirements Management and Health Management has been outlined by the author, see Figure 3.4.

The positive effect that a combination of Requirement Management and Health Management may have as a support to Quality Management can be realised in terms of the reasoning by Oakland (1993) about effectiveness and efficiency. Requirements Management may be valuable for identifying the requirements of the company’s external and internal stakeholders, in
order to decide what the right thing to do is (effectiveness). In order to assure that things go according to plan, i.e. to do things right (efficiency), Health Management may be valuable. The combined support by Requirements Management and Health Management of Quality Management is therefore believed to enhance both the effectiveness and the efficiency of an organisation, which will hopefully also lead toward the aim of Quality Management, i.e. to increased stakeholder satisfaction with a decreased amount of resources.

Figure 3.4 A theoretical Quality Management framework supported by Requirements Management and Health Management, intended to support a systemic and systematic work with continuous improvements of complex technical systems in the context of changing stakeholder requirements. Inspired by Söderholm (2003a).

The core value System View is fundamental in the framework and is applied in order to describe a stakeholder system (Checkland, 1999; Juran, 1992), a technical system (Hubka, 1982), and a joint system consisting of both man and machine (Hollnagel et al., 1995; Blanchard, 2001). The three management approaches are also related to these three systems to different extents.
The stakeholders of the technical system are viewed as elements in a stakeholder system. This system is dynamic due to changes of stakeholders, their requirements, and their interrelationships. There are also a lot of different stakeholders with a diverse set of requirements. Therefore, some methodologies and tools that support a stakeholder focus are necessary, in order to manage the requirements of this dynamic system, and thereby enable stakeholder satisfaction. This satisfaction depends on the fulfilment of stakeholder requirements related to areas such as reliability, availability, safety, environmental issues, life cycle cost, and performance. Several efficient methodologies and tools for this purpose may be found within Requirements Management.

To support continuous improvements of complex technical systems Health Management is believed to be a valuable approach. The rationale for selecting Health Management as a support to Quality Management may be found in the description made by Moubray (1997), who describes a number of important stakeholder requirements. A first point is the growing dependence on technical systems, which has led to reliability and availability having become more important. A second point is the awareness of safety and environmental issues, due to the serious negative effects that failures of technical systems have on these issues. The third point is the cost of operation and support of technical systems, which historically have increased over the years. Health Management is an approach that can improve the reliability and safety of a critical technical system, and also reduce the combined cost of operation and support throughout the life of the technical system (see, for example, Mobley, 1990; Becker et al., 1998; Litt et al., 2000; Baroth et al., 2001; Campbell & Jardine, 2001; Dunne et al., 2001; Hess & Fila, 2002). Hence, when a system is complex and critical, appropriate methodologies and tools must support the continuous improvements of it, in order to avoid unwanted effects. Health Management is an approach that provides efficient methodologies and tools for this situation.

The link from the technical system to the stakeholder system is expressed by system functions. These functions are monitored and communicated to the stakeholders as health data and information. This data and information act as facts and may be used to verify that some of the requirements of the stakeholders are fulfilled. The data and information may also be direct answers to some requirements of the stakeholders. There is also another, more physical, link between the stakeholder system and the technical system that is important to recognize. The operators and the technical system together form a joint system, the union of the two systems, as
described by Hollnagel et al. (1995). On this level there must be a correspondence between the stakeholders' requirements and the received data and information about the health of the technical system, in order for the operators to be able to properly operate the technical system. However, there must also be a similar correspondence on a more aggregated level, such as the information required by regulatory authorities.

Based on the description made above, the present writer strongly believes that Requirements Management and Health Management can support each other. However, as mentioned earlier, the two management approaches also strongly support some of the important core values within Quality Management. Requirements Management mainly supports the core value Stakeholder Focus, while Health Management primarily supports the core value Continuous Improvements. In addition to this, the two management approaches also both support the core values System View and Fact Based Decisions. The latter fact is supported through the application of appropriate measurements. The facts used to make decisions about the management of the stakeholder system and the technical system is stakeholder requirements and health data and information, respectively.

A technical system is seen as an artificial deterministic system that produces the effects necessary to achieve the transformation of operands, as discussed by Hubka (1982). The complexity of a (technical) system increases with the number of elements and the attributes and number of interrelationships between these elements (Flood & Carson, 1993). Health Management is believed to be especially valuable when the technical system of interest is a complex one. This is because Health Management enables abstraction and decomposition of the system, which is necessary in order to understand a complex system (Törne, 1996). Health data and information are measurements that represent the actual health, or appropriate indicators of the health, of a technical system, as discussed in Mobley (1990) and Campbell & Jardine (2001). It may be of interest to note that Requirements Management can probably also support the management of technical complexity (Davis & Leffingwell, 1996). The health data is necessary to make diagnoses and prognoses of a system's current and future health. On the basis of the diagnostic and prognostic information it is then possible to make decisions about appropriate operation and support actions, both current and future. Here Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support may be seen as three interdependent and suitable methodologies. These methodologies are in turn supported by appropriate tools.
The maintenance action or operation change is a response to a failure. The definitions of potential and functional failure made by Nowlan & Heap (1978) are used in this thesis. The failure is seen as an unsatisfactory condition that may be a real inability to perform a necessary function (diagnostics), or a judgement, based on physical evidence, that it will soon be unable to perform such a function (prognostics). A functional failure is the inability of a system to meet a specified performance standard (diagnostics). A potential failure is an identifiable physical condition which indicates that a functional failure is imminent (prognostics). A potential failure is thus one, which is related to the fact that the system will, within a short period of time, develop a functional failure. The failure concept discussed by Nowlan & Heap (1978) is in line with the one discussed by Lyytinen & Hirschheim (1987) and Zeithaml et al. (1990), where a failure is seen as a gap between some existing situation and a desired situation for the members of a particular stakeholder group. It seems logical to draw on the presented failure concepts and connect them to the stakeholder concept, by using the discussion about the multidimensional and dynamic nature of quality made by Garvin (1988) and North et al. (1998).

Garvin (1988) points out that it is beneficial to be aware of different approaches to quality. In order to support this awareness of different quality approaches a stakeholder focus seems appropriate, which may probably be achieved with the aid of Requirements Management. Requirements Management is seen as a systematic approach to eliciting, organising, documenting, and managing both the initial and the changing requirements of a technical system, as discussed by Davis & Leffingwell (1996). It is also believed that Health Management can support the validation of requirements, and thereby contribute to the management of requirements. User-based definitions of quality are founded on the premise that quality lies in the eyes of the beholder, and that the products that best satisfies the consumer preferences is of the highest quality (Garvin, 1988). Initially it may be favourable to have a user-based approach, when identifying the requirements that the market has. At the design stage a product-based approach can be used in order to deploy desired characteristics into specifications. Based on the reasoning about human activity systems made by Checkland (1999), stakeholders of a technical system are considered elements in a stakeholder system. The interrelationship between the stakeholders and between the stakeholders and the technical system are expressed by requirements.
3.5 *Theoretical Propositions*

The fundamental theoretical proposition that may be found in the framework above is that changing stakeholder requirements drive continuous improvements of the functions of a technical system.

A second theoretical proposition is that the combination of methodologies and tools within Requirements Management and Health Management supports the work with continuous improvements of complex technical systems.
4 RESEARCH DESIGN

In this chapter some research options and performed choices will be discussed. Areas such as research purpose, perspective, and strategy will be presented and described. Aspects of data collection and analysis will also be briefly described. In addition to this, some aspects of reliability and validity will be discussed. Finally, a roadmap that summarises the performed choices will be presented.

4.1 Research Purpose

According to Zikmund (2000), research may be classified on the basis of its purpose. Historically there are three major purposes of research (Marshall & Rossman, 1999). These purposes are to explore, describe, or explain the phenomenon of interest (Marshall & Rossman, 1999; Zikmund, 2000). See Table 4.1.

Table 4.1 Different kinds of research purposes, according to Marshall & Rossman (1999, p. 33), and how these are used in this thesis.

<table>
<thead>
<tr>
<th>Descriptive</th>
<th>Explanatory</th>
<th>Exploratory</th>
<th>The Research Purpose in this Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>To document and describe the phenomenon of interest.</td>
<td>To explain the pattern related to the phenomenon in question.</td>
<td>To investigate little-understood phenomena.</td>
<td>To explore and describe how an organisation can work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements, in order to increase stakeholder satisfaction with a reduced amount of resources.</td>
</tr>
<tr>
<td></td>
<td>To identify plausible relationships shaping the phenomenon.</td>
<td>To identify or discover important categories of meaning.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>To generate hypotheses for further research.</td>
<td></td>
</tr>
</tbody>
</table>

Marshall & Rossman (1999) state that exploratory and descriptive studies try to build rich descriptions of complex circumstances that are unexplored in the literature. Zikmund (2000) states that explorative studies are performed in order to clarify the nature of vague problems. Further on, Zikmund (2000) argues that descriptive studies are based on some previous understanding of the nature of the research problem, and tries to describe some characteristics of a phenomenon or population. Explanatory studies
try to show relationships between events and the meaning these events have (Marshall & Rossmann, 1999). According to Yin (1994), the explanation of a phenomenon is made through the stipulation of a set of causal links.

The research purpose of this study is partly of a descriptive nature since some literature that partly describes the phenomenon of interest has been found, which provides some previous understanding of it. However, the literature that has been found has often only a limited perspective on the organisational work with stakeholder focused continuous improvements of complex technical system functions. The focus in the studied literature either deals with the management of stakeholder requirements (see, for example, Davis, 1993; Macaulay, 1996; Kotonya & Sommerville, 1998) or the functions of technical systems (see, for example, Nowlan & Heap, 1978; Mobley, 1990; Stamatis, 1995; Moubray, 1997). More seldom is the focus on the combination of the two, but one exception may be found in Akao (1992). However, when a combined perspective does exist, the evolutionary nature of complex systems is often not considered (Herzwurm & Schockert, 2003). Therefore, the purpose of this thesis is also of an explorative nature. Accordingly, the purpose does not show relationships between events and the meaning of these events (that is explanatory), but explores and describes a phenomenon that is seldom, or incompletely, described in the scientific literature. See Chapter 1 (Introduction) and Table 4.1.

4.2 Research Approach

There are some aspects that a researcher should be aware of when approaching a problem and seeking answers. These approaches are often closely related to each other and to the formulated purpose of the study. Some examples of such approaches are if the study is to be founded on hermeneutics or positivism, if it is performed according to induction or deduction, or if it should be qualitative or quantitative.

4.2.1 Hermeneutics or Positivism

Hermeneutics and positivism are two dominant research approaches that not only differ in methodological aspects, but are also founded on two opposite views of life. Hermeneutics tries to find a purpose or meaning of a studied phenomenon, in order to gain an interpretative understanding of the phenomenon. Positivism, on the other hand, strives to explain a phenomenon objectively by causal relationships between dependent and independent variables. (Andersson, 1979; Denzin & Lincoln, 2001)

Arbnor & Bjerke (1994) state that there are three different methodological views. These three views are the analytical view, which is positivistic, the
RESEARCH DESIGN

system view, which to some extent is positivistic, and the actor view which
is against the positivistic ideals. The analytical view assumes that
knowledge is independent of the individuals and that the world may be
understood in an objective way in which the whole is the sum of the parts.
The system view assumes that knowledge is system-dependent, that the
whole does not equal the sum of the parts, and that the parts depend on the
system. Finally, the actor view assumes that knowledge is dependent on the
individual, and that the actors explain the whole. (Arbnor & Bjerke, 1994)

The present writer has a background in natural sciences, which contributes
to a rather strong analytical view. However, when looking upon
continuous improvements of complex technical systems the author strongly
believes that a system view is more appropriate than a strict analytical
view. When stakeholders and their requirements on the system are
included in the study an actor view, with a more hermeneutic foundation,
may very well be the most appropriate approach. However, the present
writer tries to apply a system view, with a rather strong positivistic
foundation. This system view may also reflect the author’s background in
the discipline of Quality Management. The view in Quality Management
has evolved over time, from a strict analytical view towards a more
systemic view (see Section 3.1: Quality Management). The system view of
Quality Management thereby constitutes the foundation upon which this
study is built. A further discussion about the author’s perspectives on some
selected theories may be found in Chapter 3 (Perspectives on Presented
Theories).

4.2.2 Induction, Deduction, or Abduction

In discussions concerning methodological choices, there is often a
differentiation between induction and deduction. However, induction and
deduction sometimes involve some shortcomings. Induction means that
generalisations are made from the conclusions derived from a specific case.
A weakness with this approach is that a general rule is developed from a
limited number of observations. Deduction departs from a general rule in
order to explain a specific case. A weakness here is that the approach
establishes the rule, instead of explaining it. (Molander, 1988; Alvesson &
Sköldberg, 1994)

According to Alvesson & Sköldberg (1994), abduction is used in many case
studies. With this approach a single case is interpreted with a kind of
overarching hypothetical pattern. The interpretation is corroborated with
new observations. In this way abduction may be interpreted as a
combination of induction and deduction. During the process the empirical
application is developed, and the theory adjusted. Abduction departs from empirical facts, just like induction, but does not dismiss a conceptual theoretical framework and is closer to deduction. Alvesson & Sköldberg (1994) also state that abduction is applied in medicine, in order to make diagnoses, and in fault diagnostic activities related to technical systems. See Figure 4.1.

This study is founded on a common interest in industry and academia in exploring and describing a phenomenon that is both important in practice and seems to be described in an unsatisfactory manner in the scientific literature. Hence, the study could have a deductive or an inductive approach. However, the research project, from which this study originates, is based on the industrial interest in the phenomenon. At the same time some literature must be studied in order to attain a deeper understanding of the phenomenon. Therefore, an approach that is similar to abduction seems to be appropriate for this study. The study is founded on both theoretical and empirical irregularities. After that an iterative approach between theory and practice is planned to be made in line with abduction. Finally, some theoretical contributions based on the combination of both theoretical and empirical findings will hopefully be achieved. It is also believed that the contributions can have important practical implications. See Figure 4.1.

4.2.3 Qualitative or Quantitative

Information that is conveyed by words is called “qualitative”, while information that is conveyed by numbers is called “quantitative” (Merriam, 1988). Quantitative research emphasises the measurement and analysis causal relationships between variables, not the understanding of processes (Denzin & Lincoln, 2000). In qualitative research one is interested in the
meaning and understanding of a studied process (Merriam, 1988). The use of pictures and words is often more useful, and therefore more common than the use of numbers to describe what the researcher has found during the study of a certain phenomenon. The qualitative research may therefore be seen as descriptive and holistic (Taylor & Bogdan, 1984). Marshall & Rossman (1999) state that many qualitative studies are exploratory and descriptive. However, there are also other qualitative studies that are explicitly explanatory, showing relationships between events and the meaning these events have (Marshall & Rossman, 1999). Alvesson & Sköldberg (2000) state that an important distinguishing feature is that a qualitative approach starts from the perspective and actions of the studied subjects, whereas quantitative studies proceed from the researcher's ideas about the dimensions and categories that should be focused on.

The purpose of this research is not to show relationships between events and the meaning of these events, but to try to explore and describe a phenomenon that is seldom, or incompletely, described in the scientific literature. Furthermore, this study aims not at drawing any statistical generalisations, but at gaining a deeper understanding of how the phenomenon may be characterised. The phenomenon of interest may be seen as a process, of which both the meaning and an understanding are sought for. At the same time the research project, related to this study, was initiated in an industrial setting, and not by the author. For this reason the approach of this study starts from the perspective of the studied subjects, and not from the author's ideas about what should be focused on.

The rationale for selecting a qualitative or a quantitative research approach is described in the first paragraph of this section. The situation for this specific study is described in the second paragraph of this section. By a comparison of the situation for this specific study with the conditions referred to in the first paragraph, the selection of a qualitative approach seems appropriate in order to fulfil the stated purpose.

4.3 Research Strategy

Yin (1994) describes five different research strategies to apply when collecting and analysing empirical evidence. Yin (1994) also provides three conditions to apply in order to decide upon which strategy to use. The five research strategies and the three criteria to decide upon which strategy to select are reproduced in Table 4.2. According to Yin (1994) each strategy may be used for descriptive, explanatory, or explorative research purposes.
Table 4.2 Criteria for selecting an appropriate research strategy. (Yin, 1994, p. 6)

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Form of Research Question</th>
<th>Requires Control over Behavioural Events?</th>
<th>Focuses on Contemporary Events?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>How, why</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Survey</td>
<td>Who, what, where, how many, how much</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Archival Analysis</td>
<td>Who, what, where, how many, how much</td>
<td>No</td>
<td>Yes/no</td>
</tr>
<tr>
<td>History</td>
<td>How, why</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Case Study</td>
<td>How, why</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The first criterion for the selection of an appropriate research strategy is in which way the research questions are formulated (Yin, 1994). The second research question in this study includes “how”, see Table 4.3. According to Yin (1994) possible research strategies are hence experiment, history, or a case study, see Table 4.2. The second criterion is, according to Yin (1994), if it is possible to control behavioural events or not. In this study, there is no control of behaviour events and therefore the experiment may be excluded. In addition to this, the author thinks that the combination of stakeholder requirements and corresponding system functions is of major interest, which may be difficult to study by means of an experiment. This leaves history or case study as two possible research strategies, see Table 4.2. The third criterion in the selection of research strategy is if the focus is on temporary or non-contemporary events (Yin, 1994). In this study it is interesting to look at both contemporary events and non-contemporary events. The first situation points to the case study as an appropriate research strategy while the second situation points to history as a possible strategy for the research. To answer the second research question it is possible to use a case study, a history, or both depending on which focus in time that are emphasised. The selection falls on a case study, since it may deal with the same kinds of evidence as the history, but adds the possibility of making interviews and direct observations (see Yin, 1994).

The first research question in this study includes “what”, see Table 4.3. This research question is mainly of an explorative nature and is intended to develop relevant hypotheses and propositions for further inquiry, for this reason the “what” in this question does not mean “how many” or “how much”, which would favour survey or archival strategies (see Yin, 1994, p. 5). Yin (1994) further states that it is possible to use an exploratory study...
based on any strategy to answer this kind of explorative research question. Since the second research question in this study indicates a case study as an appropriate research strategy it may be beneficial also to apply this strategy in order to answer the second research question. By applying the same research strategy in order to answer both research questions it will be possible to achieve a coordination of the performed work, which will result in saving both time and effort. Therefore, the author chose to apply the same research strategy in order to answer both research question one and research question two. The discussion about unit of analysis performed in Section 4.3.2 (Holistic or Embedded Design and Unit of Analysis) will further support this choice.

<table>
<thead>
<tr>
<th>Stated Research Questions</th>
<th>Selected Research Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>What kinds of methodologies and tools can support the work with stakeholder focused continuous improvements of complex technical system functions?</td>
<td>Case Study</td>
</tr>
<tr>
<td>How can an organisation work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements?</td>
<td>Case Study</td>
</tr>
</tbody>
</table>

### 4.3.1 Single or Multiple Case-Design

According to Yin (1994) there are four different kinds of case studies. These are single-case (holistic) design, single-case (embedded) design, multiple-case (holistic) design, and multiple-case (embedded) design.

When the same study contains more than one case the design has to be that of a multiple-case. The multiple cases should be considered as multiple experiments and not as multiple subjects in an experiment or multiple respondents in a survey. The difference between the two views of between or in experiments is revealed by the different rationales underlying the replication (experiment) as opposed to sampling (survey) logic. (Yin, 1994)

A single case study is analogous to a single experiment, and many of the same conditions that justify a single experiment also justify a single-case study. To confirm, challenge, or extend the theory there may exist one critical case that meets all the conditions for testing the theory. The single case can in this situation be used to determine if the theory’s propositions are correct or whether some alternative sets of explanations might be more appropriate. The critical case can make a significant contribution to
knowledge and extension of theory. Another situation where a single case study is appropriate is when the case represents an extreme or unique case. A third rationale for a single case is when the case is revelatory. This situation exists when the investigator has an opportunity to study a phenomenon previously inaccessible to scientific investigation. (Yin, 1994)

This study’s purpose is to explore and describe the work with stakeholder focused continuous improvements of complex technical system functions. Through the research project, connected to the National Aeronautical Research Program (NFFP), an organisation (SAAB Aerospace, Linköping) that has the responsibility for the development and evolution of a complex technical system (JAS 39 Gripen) has been accessible for scientific studies. There are only five countries in the world that develop combat aircraft. The opportunity to get access to the organisations that develop combat aircraft is hence very limited. At the same time the accessibility is very low due to both organisational confidentiality and national defence confidentiality. The present writer therefore sees the accessible case as revelatory, since there has not been any earlier opportunity to study the phenomenon of interest scientifically.

There are of course other complex and critical systems that may be of interest to study, such as chemical plants, nuclear power plants, or satellites. However, a modern combat aircraft has a context of a long life connected to a fast technological development that demands continuous improvements to an extent that these other systems do not have. In nuclear power plants, for example, the use of software is traditionally reduced to a minimum. This is done in order to increase safety and reduce the complexity, which also has the effect that the applied technology does not evolve as fast as if software should have been applied. Satellites are launched into space and, in general, not maintained or improved after that. Therefore, a modern combat aircraft and its context may perhaps even be seen as a critical case.

Modern combat aircraft have an interesting combination of a rather long life (about 30 years) and the possibility of rather easy updates due to the digitalised built-up infrastructure, which is also necessary due to a rapid technological development. JAS 39 Gripen is the only combat aircraft that is the latest in a chain of aircraft representing every new generation, which has been developed and produced in a country that has a population that is less than 50 million (Campos, 2001).
RESEARCH DESIGN

For a small non-aligned country, such as Sweden, at the height of the Cold War, a new combat aircraft was a great challenge. It was essential to increase the operational value of every airframe and to avoid building one aircraft for every role. For a nation with only eight million citizens to contribute to the defence expenditure low life cycle cost was crucial. (Silwer, 1999)

Since the end of the Cold War air power has been limited by decreasing defence budgets in most countries. Sweden faced this fact already in the seventies. So the transition from the Cold War to the new era has not been such a big change for Sweden as for many other countries. (Silwer, 1999)

The three combat aircraft Dassault Rafale, Eurofighter Typhoon, and Gripen use similar levels of technology, and may well be regarded as the latest generation (Campos, 2001). These three aircraft are the only ones belonging to the latest generation in the whole world, and out of these three, only Gripen is in operational use today. This is of paramount importance since the operational phase will probably result in changing stakeholder requirements, which in turn is believed to drive continuous improvements of the aircraft. At the same time there cannot be any monitoring and analysis of health data and information if the system is not operational. There are also some aircraft under development that may be seen as the next generation, for example the Joint Strike Fighter, which is under development in the USA. The current situation will change in the future due to both the expansion of new users of existing combat aircraft, and by the addition of other aircraft that today are in different stages of development. Today the Swedish combat aircraft and their development and evolution are both extreme and unique, due to the context that is described above.

In the discussion above it seems as if, at least, two out of three rationales for a single-case study may be considered to be fulfilled. Since the available case may be categorised as extreme, unique, and revelatory, it is decided to rule out a multiple-case study and focus on a single case. The choice of a single case study is further strengthened if one sees the case as critical, but the present writer will not make this statement.

4.3.2 Holistic or Embedded Design and Unit of Analysis

A single case study may be holistic or embedded. If the study examines only the global nature of a program a holistic design would have been used. However, the same case study may also include subunits to different
degrees. The latter situation points to the embedded case study design as appropriate. (Yin, 1994)

The phenomenon that has been set out to be explored and described is the organisational work with continuous improvements of a complex technical system in the context of changing stakeholder requirements. This phenomenon may be found in the stated purpose, which also articulates the unit of analysis (Marshall & Rossman, 1999), that is, the level of inquiry that the study will focus on. Qualitative studies typically focus on organisations, processes, groups, dyads, or individuals (Marshall & Rossman, 1999).

The stated purpose of this study indicates that the unit of analysis is a way for organisations to work systematically with continuous improvements. Since this may be seen as a process, this would suggest a holistic design. However, methodologies and tools that support the systemic and systematic work with continuous improvements are also considered important in order to understand the phenomenon that is to be explored and described. These supporting methodologies and tools may be seen as subunits of analysis.

Therefore, it seems appropriate to apply a single-case embedded design, where the main unit of analysis is the organisational work with continuous improvements of complex technical systems, and the subunit of analysis is methodologies and tools that support this work.

4.4 Data Collection

Yin (1994) discusses six main sources of evidence to apply in a case study. These sources of evidence are documentation, archival records, interviews, direct observations, participant-observations, and physical artefacts. An overview of the six sources and their comparative strengths and weaknesses may be found in Table 4.4. Three sources of evidence are considered valuable in this study, and will be described and motivated in the three following sections. The three sources of evidence that are not considered as especially appropriate for this study are archival records, participant-observations, and physical artefacts.

The data that will be collected is expected to be mainly of a qualitative nature, since the main unit of analysis is an improvement process, and the subunit of analysis is methodologies and tools that support this process. Therefore, the scales that are applied to measure the data are nominal or ordinal scales, and not interval or ratio scales (see, for example, Everitt & Dunn, 1991; Yaremko et al., 1996).
Table 4.4 Six sources of evidence and their comparative strengths and weaknesses. (Yin, 1994, p. 80)

<table>
<thead>
<tr>
<th>Source of Evidence</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation</td>
<td>• Stable – can be reviewed repeatedly</td>
<td>• Retrievability – may be low</td>
</tr>
<tr>
<td></td>
<td>• Unobtrusive – not created as a result of the case study</td>
<td>• Biased selectivity, if collection is incomplete</td>
</tr>
<tr>
<td></td>
<td>• Exact – contains exact names, references, and details of an event</td>
<td>• Reporting bias – reflects (unknown) bias of author</td>
</tr>
<tr>
<td></td>
<td>• Broad coverage – long span of time, many events, and many settings</td>
<td>• Access – may be deliberately blocked</td>
</tr>
<tr>
<td>Archival Records</td>
<td>• Same as above for documentation</td>
<td>• Same as above for documentation</td>
</tr>
<tr>
<td></td>
<td>• Precise and quantitative</td>
<td>• Accessibility due to privacy reasons</td>
</tr>
<tr>
<td>Interviews</td>
<td>• Targeted – focus directly on case study topic</td>
<td>• Bias due to poorly constructed questions</td>
</tr>
<tr>
<td></td>
<td>• Insightful – provide perceived causal inference</td>
<td>• Response bias</td>
</tr>
<tr>
<td></td>
<td>• Inaccuracies due to poor recall</td>
<td>• Inaccuracies due to poor recall</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reflexivity – interviews give what interviewer wants to hear</td>
</tr>
<tr>
<td>Direct Observations</td>
<td>• Reality – cover events in real time</td>
<td>• Time-consuming</td>
</tr>
<tr>
<td></td>
<td>• Contextual – cover context of event</td>
<td>• Selectivity – unless broad coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reflexivity – events may proceed differently because they are being observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Cost – hours needed by human observers</td>
</tr>
<tr>
<td>Participant-</td>
<td>• Same as above for direct observations</td>
<td>• Same as above for direct observations</td>
</tr>
<tr>
<td>Observations</td>
<td>• Insightful into interpersonal behaviour and motives</td>
<td>• Bias due to investigator’s manipulation of events</td>
</tr>
<tr>
<td>Physical Artefacts</td>
<td>• Insightful into cultural features</td>
<td>• Selectivity</td>
</tr>
<tr>
<td></td>
<td>• Insightful into technical operations</td>
<td>• Availability</td>
</tr>
</tbody>
</table>

Since the archival records contain quantitative data, which is not in focus in this study, it is not considered as a primary source of evidence. The selected units of analysis also make physical artefacts a source of evidence that does not seem easy to apply. This is because both the process and its supporting methodologies and tools are not believed to be possible to collect in the form of physical artefacts. Participant-observation is not believed to be a
valuable source of evidence. This is because it is probably difficult to perform participant-observations of the studied phenomenon due to a long time span, and the intra-functional nature of an organisational improvement process. However, the supporting methodologies and tools would probably be possible to study by participant-observations, but the additional value compared to direct observations is considered insignificant by the author.

4.4.1 Documentation

According to Yin (1994) there are a number of strengths and weaknesses with documentation as a source of evidence. See Table 4.4.

Yin (1994) states that information found in documents is likely to be relevant for nearly every case study topic, especially for confirming and supplementing evidence from other sources. Yin (1994) further states that documents are important in the data collection stage in a case study, due to their overall value. However, care must be taken in the interpretation of documents, since they are often prepared for another purpose and audience than that of the case study (Yin, 1994).

One strength with documentation as a source of evidence is that it is stable and therefore may be reviewed repeatedly. Documentation is also unobtrusive since it has not been created as a result of the case study. Furthermore, documentation contains exact names, references, and details of events and is hence exact. A final strength is that documentation may have a broad coverage by both a long time span, many events, and many settings. However, there are also some weaknesses with documentation as a source of evidence that must be considered. The accessibility may be low, or the access may be deliberately blocked. There may also be a bias due to an incomplete collection or reporting by the author. (Yin, 1994)

Documentation is believed to be valuable for collecting empirical evidence in this study. This is because the studied case concerns a complex and critical technical system, which probably makes documentation important for the organisation in order to be able to manage the development of the system. At the same time there are probably regulations and standards that require specific documentation. There are a number of strengths in document studies, but there are also a number of weaknesses that must be taken into consideration, see Table 4.4. One of the major weaknesses in the particular study may be that some material is probably classified as confidential, due to organisational interest or defence aspects.
4.4.2 Interviews

Yin (1994) states that interviews are one of the most important sources of case study evidence. The interview is a two-way conversation that gives the interviewer the opportunity to participate actively in the interview (Yin, 1994). The interview can focus more directly on areas that are of interest, at the same time as it is insightful and provides perceived causal inference. However, there are also a number of drawbacks that must be considered, such as bias due to the interviewer and/or respondent, see Table 4.4. According to Holme & Solvang (1991), it is important to interview respondents with the right kind of knowledge in order for the result of the study to be valid and valuable.

Interviews are a source of data that is probably very valuable in the collection of empirical data in this study. Since this study is based on a research project that is performed in cooperation with the industrial organisation that constitutes the case, it should hopefully be rather easy to identify roles and specific persons that are valuable to interview. Research considerations, such as which roles that may be interesting to interview and how to prepare the interviews, can mainly be prepared and discussed within the author's department at the university. Practical considerations, regarding what specific persons to interview and how to gain access to these persons, can be facilitated by the participation of members of the project group that work at the studied organisation.

The author thinks that a combination of document studies and interviews is valuable in order to collect data that are useful in order to gain knowledge of the studied phenomenon. By the collection of data through these two sources it is also possible to both compare and combine data from different sources, which is believed to be valuable. This is because the strengths of each source may be achieved at the same time as their weaknesses, to some degree, may be compensated for.

4.4.3 Observations

It may also be valuable to apply direct observations to some extent, but this is not believed to be a major source of evidence. This is because the present writer believes that the continuous improvement process itself is extended over time, which makes observation of limited practical value. However, supporting methodologies and tools may probably be observed in the context of their application. The observation of methodologies and tools, and the application of these are seen as building blocks of the improvement process and may hence give valuable clues in order to answer stated research questions.
4.5 Data Analysis

According to Miles & Huberman (1994), the analysis of qualitative data consists of the three activities data reduction, data display, and conclusion drawing.

There are two main strategies for the analysis of collected case study data. The first, and preferable one, is to rely on theoretical propositions, and the second is to develop a case description. Study propositions direct attention to something that should be examined within the scope of the study. Some studies may have legitimate reasons for not having any propositions. These are studies in which a topic is the subject of "exploration". However, every exploration should still have some purpose as well as criteria by which the exploration will be judged successful. Yin (1994)

The typical mode of data display in qualitative research is narrative text, although narrative text alone is sometimes considered a weak and cumbersome form of display (Miles & Huberman, 1994). However, Czarniawska (1999) states that narrative knowledge is an attractive approach in order to bridge the gap between theory and practice.

There are two major theoretical propositions that are made in this thesis. The fundamental proposition is that changing stakeholder requirements drive continuous improvements of (the functions of) technical systems. A second proposition is that the combination of methodologies and tools within approaches with different perspectives may give synergetic effects on the organisational work with continuous improvements. However, existing theories about this phenomenon very seldom cover the whole, but only parts. Therefore, it also seems appropriate to apply a case description that is founded on a theoretical framework, which combines three management approaches. The case description is in line with the descriptive part of the stated purpose, and is intended to organise the findings of the case study. It is important to notice that the two stated theoretical propositions and the theoretical framework are closely related to each other. This is because both the framework and the propositions are founded on values of the paradigm to which the present writer belongs.

Some possible methodologies for data analysis are:

- **Explanation building.** Explanation building is a special type of pattern-matching. The goal is to analyse the case study by building an explanation of the case. This analysis methodology is mainly relevant to explanatory case studies. (Yin, 1994)
• **Pattern-matching.** In the analysis of case studies, one of the most desirable methodologies is to use pattern-matching logic. Such logic compares an empirical pattern, with a predicted one based on theories. If the patterns coincide with each other, this may help to strengthen the internal validity of the case study. (Yin, 1994)

• **Time-series analysis.** In order to identify important activities in time the accomplishment of a time-series analysis may be useful (Miles & Huberman, 1994; Yin, 1994). A special form of time-series analysis is to analyse chronological events (Yin, 1994).

• **Programme-logic models.** A programme-logic model is a combination of pattern-matching and time-series analysis. (Yin, 1994)

In order to arrange the findings of the study initially, and reduce the number of them, some of the Seven Management Tools may be appropriate. These tools are compiled to aid in the analysis of qualitative data, with the exception of Matrix Data Analysis, which is equivalent to Principal Component Analysis. See, for example, Mizuno (1988).

In order to analyse the findings of the case study further the theoretical framework that was presented in Chapter 2 (Theoretical Frame of Reference) is intended to be applied. The framework is based on a combination of theories within Quality Management, Requirements Management, and Health Management. Hence, the theoretical framework can help to structure the empirical findings from the case study. This theoretical framework may perhaps be regarded as related to a pattern-matching logic, but probably more accurately to a case description.

Also a Programme-Logic Model that summarises a pattern matching logic based on some management perspectives and appropriate time-series may also be applied in the data analysis, see Table 4.5. Management perspectives that may be applied are Quality Management, Requirements Management, and Health Management. The time-series may be based on two chronological orders, represented by the four phases of the Improvement Cycle (Plan-Do-Study-Act, see Deming, 1993), and the phases of the system life cycle (exemplified by the description found in ISO/IEC 15288). The four phases of the Improvement Cycle may be considered a description of the improvement process on a system level, which is the main unit of analysis in this study. The three management perspectives include methodologies and tools, which are the two subunits of analysis. A further extension of the model could be to include values in the three management perspectives as well. See Table 4.5. However, in this study the Programme-Logic Model is not intended to be applied in any formal
analysis since the research purpose is not of an explanatory nature. The model may anyway illustrate how the present writer looks upon the studied phenomenon.

Table 4.5 Suggestion of a Programme-Logic Model that could have been applied in the analysis of empirical data related to this study, if the purpose had been explanatory. The model includes a combination of a time-series and three management perspectives. The time-series is based on two chronological orders, of which the Improvement Cycle may be regarded as a description of the improvement process on a system level, which is the main unit of analysis. The three management perspectives include methodologies and tools, which are the two sub units of analysis. A further extension of the model could be to include values in the three management perspectives as well.

<table>
<thead>
<tr>
<th>Chronological Orders</th>
<th>Management Perspectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improvement Cycle</td>
<td>System Life Cycle</td>
</tr>
<tr>
<td>Plan</td>
<td>Concept</td>
</tr>
<tr>
<td></td>
<td>Development</td>
</tr>
<tr>
<td>Do</td>
<td>Production</td>
</tr>
<tr>
<td>Study</td>
<td>Utilisation</td>
</tr>
<tr>
<td></td>
<td>Support</td>
</tr>
<tr>
<td></td>
<td>Retirement</td>
</tr>
<tr>
<td>Act</td>
<td></td>
</tr>
</tbody>
</table>

4.6 Research Quality
Yin (1994) discusses four different ways of judging research. These are reliability and three different kinds of validity. A summary of tactics for affecting these measures positively may be found in Table 4.6.
Table 4.6 Case study tactics for four design test. Original source COSMOS corporation, as referred to by Yin (1994, p. 33)

<table>
<thead>
<tr>
<th>Tests</th>
<th>Case Study Tactic</th>
<th>Phase of Research in which Tactic Occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construct Validity</td>
<td>Use multiple sources of evidence</td>
<td>Data collection</td>
</tr>
<tr>
<td></td>
<td>Establish chain of evidence</td>
<td>Data collection</td>
</tr>
<tr>
<td></td>
<td>Have key informants review draft case study report</td>
<td>Composition</td>
</tr>
<tr>
<td>Internal Validity</td>
<td>Make pattern-matching</td>
<td>Data analysis</td>
</tr>
<tr>
<td></td>
<td>Make explanation-building</td>
<td>Data analysis</td>
</tr>
<tr>
<td></td>
<td>Make time-series analysis</td>
<td>Data analysis</td>
</tr>
<tr>
<td>External Validity</td>
<td>Use replication logic in multiple-case studies</td>
<td>Research design</td>
</tr>
<tr>
<td>Reliability</td>
<td>Use case study protocol</td>
<td>Data collection</td>
</tr>
<tr>
<td></td>
<td>Develop case study data base</td>
<td>Data collection</td>
</tr>
</tbody>
</table>

4.6.1 Construct Validity
To meet the test of construct validity it is mandatory to cover two steps (Yin, 1994):

- Select the specific types of units that are to be studied (in relation to the original objectives of the study).
- Demonstrate that the selected measures of the units indeed reflect the specific types of units that have been selected.

In the performed case study two types of units to study have been selected. These units are (1) two subunits of analysis, i.e. methodologies and tools that support the work with continuous improvements, as reflected by the first research question, and (2) the main unit of analysis, i.e. the organisational work with continuous improvements, as reflected by the second research question. There are a number of tactics to demonstrate that the selected measures of units reflect the units of analysis, which will be discussed in the remaining part of this section.

There are three tactics available for increasing construct validity. These are (Yin, 1994):

- The use of multiple sources of evidence (during data collection).
- Establish a chain of evidence (during data collection).
• Have the draft case study report studied by key informants (during composition).

In the case study document studies and interviews have been selected as two major sources of evidence, in order to affect the internal validity positively. This application of multiple sources of data is called data triangulation, and by using multiple perspectives on the same data set a theory triangulation can also be achieved (Yin, 1994). Since the collected data is planned to be looked upon through theories from three management perspectives, the construct validity should be affected positively. The multiple perspectives are achieved through the management framework presented in Chapter 3 (Perspectives on Presented Theories) and the Programme-Logic Model presented in Table 4.5. Since the research approach is founded on abduction, a chain of evidence may be possible to establish. The chain of evidence may also be enhanced through a clear description of the study, from stated research questions to case study conclusions, which would also contribute positively to the study’s reliability. The author also plans to have drafts of the case study report studied by key informants, which should also contribute positively to the construct validity. However, one risk that must be calculated with is that the key-informants may have little time available for the study of drafts of the case study report.

4.6.2 Internal Validity

Internal validity is only a concern for explanatory case studies, where causal relationships between variables are studied. In exploratory and descriptive studies, where the causal relationships are not considered, the internal validity is not applicable. (Yin, 1994)

The performed case study is not of an explanatory character, and hence the concept of internal validity is not relevant. However, the Programme-Logic Model presented in Table 4.5 may be applied in order to understand how the present writer looks upon the studied phenomenon. The Programme-Logic Model, which includes both pattern-matching and a time-series analysis, based on chronological orders also indicates one possibility of further research.

4.6.3 External Validity

External validity deals with the problem of knowing whether a study’s findings are possible to generalise beyond the performed case study. The external validity for case studies deals with analytical generalisation. This
means that some of the results of the case study are generalised to some broader theory. (Yin, 1994)

The analytical generalisation demands that the theory is tested through replications of the findings in other cases, where the theory has stated that the same thing will occur. This logic of replication is the same as for experiments, where the scientist can generalise from one experiment to another. (Yin, 1994)

The external validity of the theories developed in this thesis is not planned to be tested on a completely different case. However, the findings of the case study are planned to be tested in a limited application in the studied case. Since the findings of the case study are combined with some theoretical findings into a description of how an organisation can work with continuous improvements, the external validity of this result may hopefully be corroborated by the application.

4.6.4 Reliability
Reliability is a general term denoting consistency of measurements derived from repeated observations of the same subject under the same circumstances (Yaremko et al., 1986). Yin (1994) states that reliability demonstrates that the operations of a study, such as the data collection procedures, may be repeated with the same results. The author thinks that it may be valuable to compare reliability with precision. Precision in measurement is defined as having small measurement errors, as indexed by the standard deviation (Yaremko et al. 1986). The more precise a measuring instrument is the smaller standard deviation of the values obtained from repeated measurements of an object (Yaremko et al., 1986).

In order to affect the reliability positively Yin (1994) recommends that a case study protocol and a case study database are constructed. The present writer intends to construct a case study database with the aid of a software program, ordinary folders with indexes, or a combination of both. However, due to some data probably being classified as confidential, in regard to organisational interest or defence aspects, the reliability of the study may be affected negatively. This is because persons outside the project group may have difficulties in getting access to some of the documents. In order to reduce the negative influence on the reliability, the author intends to find sources of evidence that are not classified, but that have corresponding information as the sources that are classified. In order to affect the reliability positively a case study protocol will be developed.
To further strengthen the reliability the author will try to write the thesis in such a way that transparency and inter-subjectivity are achieved.

4.7 Summary of Methodological Choices

In Figure 4.2 considered and performed methodological choices in this study are summarised. The shadowed areas show which choices have been performed. The arrows illustrate in what order the choices have been carried out. This order of choices also coincides with the order of sections in this chapter.

![Diagram of methodological choices]

Figure 4.2 Summary of considered and performed methodological choices in this study. Performed choices are marked by shadowed areas. Arrows illustrate in what order the choices have been performed, which also coincides with the order of sections in this chapter.
PART II: THE EMPIRICAL WORK AND FINDINGS

CHAPTER 5: RESEARCH PROJECT AND RESEARCH PROCESS
In this chapter the background to the research project and the phases of the research process will be described.

CHAPTER 6: CASE DESCRIPTION
This chapter will start with a short presentation of some general background information about the studied case. After that, the case will be described in accordance with the perspective on the presented theoretical framework of the study, with special focus on methodologies and tools for Requirements Management and Health Management. The description is founded on data and information that have been collected through document studies, interviews, literature studies, and observations.
5 RESEARCH PROJECT AND RESEARCH PROCESS

In this chapter the background to the research project and the phases of the research process will be described.

5.1 Background to the Research Project

Sweden has a rather long history of developing national civil and military products in aeronautics. There is also a close collaboration in research and development issues between users, industry, academia and agencies as well as an integrated civil and military aeronautics research community. (Langemar & Gustavsson, 2001)

The members of the Swedish aeronautics research and development are the industry and the government. SAAB, Volvo Aero Corporation (VAC), and Ericsson Microwave (EMW) dominate the industrial side. The Swedish Defence Material Administration (FMV), the Swedish Defence Research Agency (FOI), and universities are actors on the governmental side. (Langemar & Gustavsson, 2001)

The Swedish Air Force is important as a developer of defence system requirements, and thereby directing support to basic aeronautical research. FMV has the responsibility for the design of defence systems, procurement of defence material, administration of the Air Force Technology Development program and the National Aeronautics Research Program (NFFP), which is a joint civil and military undertaking. FOI is the result of the merger between the Aeronautical Research Institute of Sweden (FFA) and the Swedish Defence Research Establishment (FOA). The FOI organisation has aeronautics related activities in four divisions. Several universities participate in national programs and are important parts of the technology transfer between disciplines and between research and application. (Langemar & Gustavsson, 2001)

The research project, related to this study, is within the framework of the National Aeronautics Research Program, project number NFFP3-481. The project is performed in close cooperation between the Centre for Dependability and Maintenance, represented by the Division of Quality & Environmental Management, at Luleå University of Technology, and SAAB Aerospace in Linköping.
5.2 The Research Process

The research process may be looked upon through the four phases of the Improvement Cycle (Plan-Do-Study-Act), as described by Deming (1993). See Figure 5.1.

![Diagram of the Improvement Cycle]

**Figure 5.1** The research process of this study illustrated by the Improvement Cycle. In this thesis one lap around the cycle is presented. The dotted lines describe how future research can be performed on the basis of the results of this study.

5.2.1 Plan

In the Plan phase preliminary formulations of the research purpose and research questions were decided upon. The stated purpose and research questions were based on a research proposal that had been constructed in the project group, which consisted of participants from both the university and the industrial organisation.

Based on the purpose and research questions the research to be done was designed. This work was mainly done within the university. As a support for the work an initial literature study was made and meetings in the
university and the industrial organisation that were involved in the research project were arranged. The initial literature study and the outcomes of meetings established a foundation for the research. For this reason it was tentatively decided what to do, how to do it, and why it should be done. However, these statements, the purpose, and research questions were slightly modified and sharpened during the progress of the research. This was done in response to increased knowledge that was gained throughout the Do phase, which is described in the next section.

The result of the Plan phase may be found in Chapter 1 (Introduction) and Chapter 4 (Research Design).

5.2.2 Do
The research done in the Do phase consists mainly of a literature study and a case study, which were performed in parallel, in order to support each other. See Figure 5.2.

The reason for the research was based on industrial interest with regard to diagnostic and prognostic capabilities, in the context of a rapid technological development and expanded customer diversity. Therefore, a literature study focusing on tools for diagnostics and prognostics was initiated. The literature search was based on some initial search words that were generated during a brainstorming session, which was used in order to trigger the literature study. After the brainstorming session an initial literature search was conducted, based on the initial search words. The initial literature search was made through the use of some databases and search engines. The databases were selected through descriptions of their contents, the selection of the search engines were more of an ad hoc character. The initial literature search resulted in some abstracts that were read through. When interesting abstracts were found the corresponding literature was retrieved. In addition to the abstracts some new search words also emerged. In addition to making an inventory of tools that support diagnostics and prognostics interfacing methodologies were also explored. This was done in order to get a broader picture and thereby increase the knowledge of the studied area. The combination of methodologies interfacing to diagnostics and prognostics, and supporting tools, pointed to an approach that is sometimes called Health Management as being appropriate for describing and summarising this initial phase of the literature study.

In addition to the literature study, an applied approach to Health Management was studied in the available case. Data was collected mainly
through interviews and document studies, even though some direct observations were also made. The documents were searchable, and to a large extent available, in electronic form, through an intranet. This made it easy to apply the same initial, and emerging, search words as in the literature study. The studied case also includes a vast number of interrelated processes. Fortunately, these processes are mapped and documented electronically, and retrievable through the intranet. Processes of interest to this study were identified through search words given by the literature study and applied to the company’s search engine on their intranet. In this way the parallel work with case study documents and literature studies made them support each other. When different kinds of obstacles or questions emerged the author had the opportunity to discuss them initially with persons in the organisation, who were included in the project group. If further questions still remained other persons in the organisation could be identified and contacted. This approach resulted in an iterative work process between document studies and interviews.

The interviews were semi-structured and have been made with one person and up to 10 persons at a time. Interviews with a small number of persons attending often had the purpose of clarifying things on a rather concrete level, such as the application of specific methodologies and tools, or one or a few stakeholder perspectives. Interviews with a large number of persons attending were arranged as meetings, or brainstorming sessions. The purpose of the brainstorming sessions was to gather persons with different expertise and generate a vast number of ideas and structure these when more complex problems emerged, such as cross-functional processes and the combination of different stakeholder perspectives. The documentation of the interviews were notes that included date, attending persons, initial problems or questions, and corresponding solutions or answers. However, all conversation is not documented since some conversations took place on an ad hoc basis, when they were considered necessary in order to proceed in the research. In all cases the respondents or participants received some information in advance, so that they knew what the purpose of the interview was and that it was performed within the framework of the research project. It was also important to let the respondents read the notes in order to validate that these corresponded with what the respondent had said.

Most of the interviews were made at SAAB, but some complementary ones took place at the North Bothnian Wing (F21) of the Swedish Air Force. The stakeholders that have been interviewed may be classified into two major categories. The first category is those responsible for the design and
evolution of the technical system and its support system, and the second category those that are operating or are affected by the designed systems. The stakeholders responsible for the design and evolution of the system that were interviewed are persons working with different subsystems of the aircraft, such as monitoring and testing, registration, and the fuel system. Other persons are those working with system integration, reliability, safety, and logistics issues. Also persons working with the verification and validation of contractual requirements have been interviewed. In addition, experimental test pilots and field service representatives in the developing organisation have been interviewed. Examples of operators of the systems that have been interviewed are technicians, maintenance planners, and quality assurance people. Persons that have been working with flight safety investigations have also been interviewed. The main theme of these interviews was the requirements on data and information received from the monitoring and test system.

The focus in Health Management is mainly on how to manage the health, or condition, of a technical system. In order to know what the tolerable health of the system is, one has to consider the requirements of the system's stakeholders, which was one of the findings when the approach of Health Management was studied. Therefore, the second phase of the literature study was directed towards methodologies and tools for the management of stakeholder requirements, i.e. Requirements Management. Empirical data about the work with, and experiences of, Requirements Management was collected through the case study, in the same iterative way as described earlier, in the case of Health Management.

Literature with interesting abstracts, that were practically retrievable, was read through as a whole and analysed. Books and other extensive literature were only partly read through. The literature study resulted in a number of books, conference proceedings, theses, technical reports, electronic sources, and articles in journals, magazines and newspapers. Literature that contained information that was considered valuable for the implementation of the research purpose was collected in a reference library. The library was composed with the aid of bibliographic software. Articles in the reference library got a call number and were placed in folders. In addition, articles that could be retrieved as electronic copies were also linked to the library. Documents from the case study were treated in the same way as in the literature study.

In addition, continuous discussions with the industrial partner in the project, and discussions with colleagues at the university were performed.
These discussions were mainly about methodological issues related to the research, and hence gave valuable support to the research.

The findings of the literature study may be found in Chapter 2 (Theoretical Frame of Reference). The empirical findings of the case study may be found in Chapter 6 (Case Description).

5.2.3 Study
In this phase of the research process the theoretical and empirical findings were analysed.

As a first step, the result of the two phases of the literature study (Health Management and Requirements Management) was analysed through a filter of theories from Quality Management, and primarily the management system view, as described by Hellsten & Klefsjö (2000). This analysis was supported by using Affinity Diagram (see Mizuno, 1988), which was applied as a tool in order to initially reduce and structure the theoretical findings into groups of methodologies and tools. In order to further analyse the material the Relationship Diagram (see Mizuno, 1988) was applied. Main relationships between methodologies and tools were given by the management system view of Quality Management. More detailed relationships were given by theories in Requirements Management and Health Management. The results of this initial analysis were two theoretical frameworks that described Requirements Management and Health Management. As a final analysis of the theoretical findings, the three management approaches were combined into one unifying theoretical framework. This theoretical framework acted as a foundation for a description of empirical findings within the studied case. On the basis of the theoretical findings a Programme-Logic Model was also created, that can support the analysis of empirical findings when the research purpose is explanatory, as described by Yin (1994).

Based on the theoretical framework and the findings of the case study, a model intended to support the work with continuous improvements was created. The model was intended to be applicable when deciding upon what functions within a complex technical system to cover with health management technologies, based on stakeholder requirements. The model was mainly based on ideas from four existing methodologies (Quality Function Deployment, Failure Mode & Effect Analysis, Reliability Centred Maintenance, and aspects of system safety as described in MIL-STD-882C), which were adapted and combined in order to reflect the chosen focus on the combination of stakeholder requirements and system functions.
Furthermore, a toolbox with a number of identified tools that seemed appropriate for supporting the methodology was described. In addition, adaptation of one methodology and a closely related tool were made. The methodology is Failure Mode & Effect Analysis (FMEA) and the tool is the FMEA-sheet.

In this phase of the research continuous formal and informal meetings with industry and colleagues at the university were also arranged.

The analysis of empirical and theoretical findings and the results of this analysis may mainly be found in Chapter 7 (Analysis and Results). Some results of the analysis of theoretical findings may be found in Chapter 3 (Perspectives on Presented Theories). Moreover, the three papers that are appended to this thesis contain summaries of parts of the results of the performed study.

5.2.4 Act
In this final phase, the results of the performed study are discussed in terms of reliability and validity. The contents of previous chapters are reviewed and some suggestions for further research are discussed. See Chapter 8 (Conclusions and Discussion).

5.2.5 Summary of Activities and Outcomes
The performed activities and achieved outcomes of the research may be illustrated as in Figure 5.2. The activities are related to the four phases of the improvement cycle, and the outcomes are related to the chapters of this thesis. However, during the performed work the chapters may be viewed as working papers since they were not completely finished. But the contents of these working papers acted as a means of communication with persons included in the project group in the industrial organisation and colleagues at the university.

It is also important to notice that the work has been carried out in an iterative manner between the four phases, and not necessarily as functionally as it may appear in Figure 5.2. At the same time the chapters of this thesis may not be the best way of illustrating the outcomes of the performed work in different phases. However, in order to clarify the performed work and achieved outcomes in each phase the author believes that Figure 5.2 may act as a support. This is because the author wishes that it should be possible to read the thesis without any additional material, in order to understand what has been done and what the results are.
**Figure 5.2** The research process, described by the four phases of the Improvement Cycle, and included activities and outcomes illustrated by the chapters of this thesis.
6 CASE DESCRIPTION

This chapter will start with a short presentation of some general background information about the studied case. After that, the case will be described in accordance with the perspective on the presented theoretical framework of the study, with special focus on methodologies and tools for Requirements Management and Health Management. The description is founded on data and information that have been collected through document studies, interviews, literature studies, and observations.

6.1 Technical System

The technical system that has been studied is the Swedish combat aircraft JAS 39 Gripen, which in the following is named aircraft 39. How the study was planned may be found in Chapter 4 (Research Design). A short description of the related research project and how the study was actually performed may be found in Chapter 5 (Research Project and Process).

6.1.1 Background


For a small non-aligned country at the height of the Cold War, a new combat aircraft was a great challenge. It was essential to increase the operational value of every airframe and to avoid building one aircraft for every role. For a nation with only eight million citizens to contribute to the defence expenditure a low life cycle cost was crucial. (Silwer, 1999)

As a result from the studies it was decided that the new aircraft system should meet two design requirements (Bååthe, 1995):

- A multi-role aircraft that was capable of performing three main missions that were defined by the Swedish Air Force (intercept, strike, and reconnoitre).
- A small aircraft with a single and modularised engine.

In addition to the design requirements the aircraft system should also meet some other major requirements. One of these was that the aircraft had to be easily maintained by personnel with only a limited period of training (conscripts), at dispersed road bases (Sandberg & Strömberg, 1999). The
Swedish concept of using dispersed road bases for flying operations puts a unique demand on maintenance and reliability (North, 1999).

Based on stated requirements, different analyses and simulations of tactical, technical, and availability performance were carried out. These analyses and simulations formed the basis of a technical specification that was sent out in a request for proposals to aircraft manufacturers, both within and outside Sweden. (Sandberg & Strömberg, 1999)

After negotiations a Swedish consortium called IG JAS (Industry Group JAS) was selected as developer of the new combat aircraft (Sandberg & Strömberg, 1999). The decision for procurement of a Swedish built combat aircraft was taken by the Riksdag in 1982 (Silwer, 1999).

A contract between the Swedish Defence Materiel Administration (FMV) and IG JAS (Industry Group JAS) was signed and the combat aircraft project JAS 39 Gripen was established (Sandberg & Strömberg, 1999).

The Swedish aerospace industry and the Swedish Air Force have a rather unique vendor and customer relationship. This is due to the fact that the industry has been developing and delivering military aircraft to the air force since the 1930s. The close relationship secured an early focus on availability performance and support cost over the product’s life cycle during the development of aircraft 39. It was clearly stated that the aircraft should not only be a high performance aircraft, but it should also be cost effective. The aircraft was required to break a steep climb in life cycle cost, at the same time as availability performance and combat performance should be improved. (Sandberg & Strömberg, 1999)

The Swedish Air Force has today ordered 204 aircraft, including about 30 fully operational two-seaters. The order is a package containing aircraft, weapon systems, ground support systems, electronic warfare systems, training, overhaul, maintenance, development, modifications, and future growth potential. (Silwer, 1999)

Instead of a pre-planned midlife update, Sweden has planned a continuous process of inserting new technology into the aircraft (Morrocco & Taverna, 2001). An upgrade program of the aircraft is running and a new edition will become operational almost annually (Silwer, 1999). This continuous process is supported by the Swedish government through financial support to a number of technological developments that will be added to the aircraft once they mature (Morrocco & Taverna, 2001). The evolutionary strategy is
to a large extent possible due to the fact that aircraft 39 is, to a much larger degree than its predecessors, a software aircraft (Silwer, 1999).

Today, IG JAS (composed of SAAB, Volvo Aero Corporation, Ericsson Microwave Systems, Ericsson SAAB Avionics, and Celsius Aerotech) is working together with BAE SYSTEMS in order to further develop the aircraft and its support system. This work is done in order to secure that the combined system effectiveness and life cycle cost are kept in control also in the future. (Sandberg & Strömberg, 1999)

6.1.2 Description

High combat value and flexible use at the lowest possible cost have been a primary goal at the development of aircraft 39. This has been possible to achieve by the application of advanced technology, modern materials, and a modern production. (FMV, 1999)

Aircraft 39 has three main missions to perform, namely, interception, striking, and reconnaissance. Aircraft 39 is also the first light unit airplane that does not need any physical configuration to act in the three different kinds of missions. (FMV, 1999)

The aircraft is composed of about 60,000 details. In order to combine all subsystems within the aircraft there are about 30 kilometres of electrical wiring. The aircraft also includes about 40 computers that together control about 450 different apparatus. (Ahlgren et al., 1998)

Aircraft 39B is a two-seater version that has no automatic gun, but is otherwise compatible with the single-seater version 39A (FMV, 1999). See Table 6.1 for some data about the two versions of aircraft 39.

Table 6.1 Some dimensional, weight, and performance data for the two versions of aircraft 39. From (FMV, 1999)

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Single-seater</th>
<th>Two-seater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wingspan (including launchers)</td>
<td>8.4 m</td>
<td>8.4 m</td>
</tr>
<tr>
<td>Length (excluding pitot tube)</td>
<td>14.1 m</td>
<td>14.8 m</td>
</tr>
<tr>
<td>Height Overall</td>
<td>4.5 m</td>
<td>4.5 m</td>
</tr>
<tr>
<td>Wheel Track</td>
<td>2.4 m</td>
<td>2.4 m</td>
</tr>
<tr>
<td>Wheel Base</td>
<td>5.2 m</td>
<td>5.9 m</td>
</tr>
</tbody>
</table>

Weights and Performance

Max Take-off Weight: Approximately 14 tons
Max Speed: Supersonic at all altitudes
The electric system in aircraft 39 consists of different articles of equipments that are interconnected. One main computer handles the main logic and most of the functions that are related to the integration of operator and aircraft. The requirements for a cost effective and easy way of modifying the aircraft, both the basic aircraft systems and the tactical systems, are to a large extent met through the possibility of making software changes in the computerised equipment. A majority of the subsystems are controlled, monitored, and tested by built-in computer controlled electronic units. The computer integration makes it possible to (FMV, 1999):

- Shift between different combat missions.
- Easily and cost effectively change the aircraft’s system construction to be able to meet future changing threats and tactical requirements.
- Easily locate failures in the systems in the aircraft.
- Keep the maintenance cost low.

Aircraft 39 is built to be able to meet rapidly changed requirements in a conflict situation. Changes between the three different kinds of missions can be made without any modification of the aircraft or software functions, and even during performed mission, if applied loads so admit. The requirements for flexibility have been met by including tactical system functions in the software. A large number of alternative functions are always available and can quickly be chosen. The requirements on flexibility are further met by an electronic presentation system with an integrated flexible manoeuvring. This allows a vast number of presentations and manoeuvring modes that are adapted to the requirements of different tactical scenarios. (FMV, 1999)

Safety performance has been considered through redundancy in hardware, as well as in software, in the aircraft’s control and supply systems. The aircraft is light, partly due to composite materials that are included in the aircraft’s structure. The aircraft is adapted to Swedish dispersed road bases and can operate from short and narrow runways. The aircraft is also self-supporting through a built in Auxiliary Power Unit (APU). (FMV, 1999)

Since the operational life of a combat aircraft is 20 to 30 years the costs of operation and support will make up an essential part of the total life cycle cost of the aircraft. These costs have been minimised in the case of aircraft 39 through a number of cost effective system solutions and components, and through a design of the aircraft aiming at low maintenance costs. The maintenance has been directed towards corrective maintenance. (FMV, 1999)
There are some major results regarding logistic aspects that are included in aircraft 39. They are examples of solutions that are intended to achieve higher availability performance and lower life support cost. The aircraft is (Sandberg & Strömberg, 1999):

- Built around computerised and modular subsystems, which increased the reliability performance at the same time as the size and weight of the aircraft was reduced.
- Computerised to a level that has enabled microelectronics, with extremely high reliability, to replace analogue and mechanical systems to a large extent.
- Designed on a modular concept, based on Line Replaceable Units (LRUs), which makes it easy to replace a faulty unit. The faulty unit can then be repaired on site or elsewhere as part of a normal logistic flow. The LRUs that have the highest failure rate are placed in such a way that the accessibility is high, in order to facilitate their replacement.

The aircraft also has (Sandberg & Strömberg, 1999):

- A single, modular engine that is both durable and easily accessible. The engine design contributes to easily performed inspections and replacements of engine modules. Even a complete engine change can be carried out in a short time at a dispersed road base.
- A long Mean Time Between Maintenance, due to few and simple maintenance actions.
- A small number of necessary tools and maintenance equipment. As one example, no tools are required to open and close the service panels.
- All lamps, indicators and switches needed during the turnaround are placed in the same area of the aircraft. The connections for fuel and communication with the pilot are also located at the same place.
- Functional Monitoring, Reconfiguration Management & Built In Test (FM/RM & BIT), which simplifies gathering and processing of operational data.
- Totally integrated computer systems, which makes it possible to perform upgrades more quickly and easily than ever before.

6.2 Requirements Management

The application of Requirements Management that has been studied is related to the organisation which is responsible for the development and evolution of aircraft 39. A special focus is on how Requirements Management is applied in order to achieve traceability between stakeholder
requirements and critical functions of the technical system that should be covered by tools within Health Management. These tools support the methodologies of Condition Monitoring and Diagnostics & Prognostics, which are included in Health Management. The methodology of Condition Based Operation & Support is primarily seen as related to the stakeholders of the technical system, and thereby seen as a generator of requirements. However, in a technical system there may also be some tools that support Condition Based Operation & Support.

6.2.1 Some Organisational Aspects

In a big industrial organisation the collection of requirements can be performed at different levels and functional departments. This dispersed collection of requirements may make it difficult to get one unified picture of all requirements. Another, related difficulty may be if there is a partition into one group of people that design and produce the aircraft, while another group of people have to verify that the requirements of the contract are fulfilled. With a partition into different functional responsibilities it is possible that requirements are formulated from a design perspective, without considering how they can be verified. There may also be a partition into people designing the technical system, and people designing the support system. However, in order to design a combined system that is as good as possible there must be close cooperation between those developing the technical system and those developing the support system.

It is important to have one overarching tactical, technical, and economic picture of the requirements on the product, from which other requirements are derived. The product includes both the technical system and the support system and it is the combination of the two systems that should be related to the overarching requirements. When the product life cycle is long, documentation that enables traceability of requirements is very important. A long product life results in the need of continuous improvements and developments that require control over changes that have been made and their consequences. At the same time the persons that are responsible for the original design of the product may retire or give notice, which means that knowledge of the product may be lost. Hence, good requirement documentation is crucial in the development of complex technical systems and their support systems.

Requirements may also be unclear, which makes it necessary to interpret them in some way. Therefore, it is very important to be aware of what characterises a good requirement. At the same time different stakeholders may have conflicting requirements that must be managed in a systematic
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way. Examples of stakeholders are authorities, customers, operational and maintenance analyses, and the general public. Society has legal requirements, for example on environment and taxes, but also more tacit requirements on the organisation's contribution to employment. Different authorities have requirements, as representatives for society, on issues such as environment and safety. Requirements from authorities are related to airworthiness, environmental issues on both the product, such as disposal and recycling, and the production and business. Customers have requirements on the product, but also on the production and business. Examples of standards that are followed are ISO9000, ISO14000, Federal Aviation Regulations (FAR), Joint Aviation Regulations (JAR), and Regulations for Military Aviation (RML).

There are different ways of prioritising requirements of which one simple way is to divide them into mandatory requirements and those that should be met. It is also important for requirements to be traceable in order to be able to see which stakeholders have formulated them. One example of when the traceability may be lost is when external requirements are included in internal instructions, which may make the requirements to appear as internal. Thereby, the requirement may very well be fulfilled, but nobody knows about it and it can become almost impossible to verify the original external requirement.

Another difficulty is if requirements are treated as confidential, which makes it difficult to get access to them and their traceability may thereby be reduced. The confidentiality also makes it difficult to derive requirements from an overarching picture of requirements, which should act as the foundation of all requirements related to the product. This overarching picture of requirements should preferably be available to everyone, in order to understand the origin of requirements on different levels in the product and the relationship between requirements on systems on lower levels. In order to support this in practice an appropriate software program is almost necessary.

In the industrial organisation there are a vast number of processes, instructions, and manuals that are available through an intranet. These documents describe such things as how different functional departments are interrelated, how the work should be carried out, and what support to apply. The descriptions range from strategic level down to operational level. However, there may also be some confidential issues that may be difficult to manage.
6.2.2 Product Life Cycle

The Product Life Cycle at SAAB consists of ten phases, see Figure 6.1. A product may be the combination of both a technical system and its support system. During the life cycle of the product a number of design reviews are made in order to check that stated requirements are fulfilled. Also a number of different baselines are designed. (Sandberg & Strömberg, 1999)

Figure 6.1 The Product Life Cycle at SAAB, consisting of ten phases with some examples of Configuration Baselines and Design Reviews. From Sandberg & Strömberg (1999, p. 326).

The aircraft, which is the technical system of the product, consists of a number of subsystems, which may be further deployed into smaller elements. The systems and subsystems also have life cycles that must be related to the Product Life Cycle. However, the earlier phases of the system and subsystem life cycles must be shorter than that of the product. The further down in the system hierarchy the deployment is made the shorter each phase becomes, at the same time as the number of parallel life cycle phases increases. The number of life cycles increases with decreasing system hierarchy since one technical system consists of a number of subsystems, which each in turn consists of a number of elements. See Figure 6.2.

SAAB has a standard that describes and defines the product life cycle (STD 4220E). The phases of the product life cycle are based on the description made in ANSI/EIA-649. The phases described in ISO/IEC correspond also well with the phases of the product life cycle as described by SAAB. These standards may be seen as tools that support the work related to different phases of the product life cycle.

In order to enable traceability of requirements between and in each system level different requirement documents are constructed. See Figure 6.3. Requirements on aircraft level, stated in the Product Specification, are broken down and classified according to MIL-STD-882C (hardware) or
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RTCO/DO-178B (software). However, the classification of hardware is also complemented by an additional classification into hidden or evident failures, as described in MSG-3.

![Diagram of life cycles for product, systems, and subsystems]

**Figure 6.2** The relationship between the life cycles for the product, systems, and subsystems. It is important to understand that there are several parallel lifecycles for systems and subsystems, even though this is not shown in the figure. Inspired by SAAB (2002a).

In the case of aircraft 39 a great number of efforts were put in the deployment of contractual requirements, stated in the Product Specification, from aircraft level to subsystem level before an agreement was reached. The aircraft was hardly defined, but based on experiences from earlier aircraft it was rather clear what subsystems should be included in the aircraft. Based on experiences it was also known what contribution each subsystem was supposed, and allowed, to give to aircraft level requirements. (Sandberg & Strömberg, 1999)

The predictions of subsystem contributions to aircraft level requirements were more or less accurate. However, since some subsystems turned out to be better than predicted, while other subsystems turned out to be worse than predicted, the requirements on aircraft level were fulfilled. The aircraft even turned out to supersede the original contractual requirements. (Sandberg & Strömberg, 1999)
Figure 6.3 Documentation, in order to enable traceability of requirements between and within different system levels of the product. Inspired by SAAB (2002a).

Three examples of aircraft level requirements are the budget of failure intensity, Mean Time Between Failures (MTBF), and the probability of loss of aircraft, which is stated in the Product Specification. The budget of failure intensity is divided on subsystem level based on, for example, experiences from earlier aircraft, operational and maintenance conditions, and the system design. Examples of measurements that are deployed to subsystems are MTBF and probability of loss of aircraft. These measures are divided into an acceptable level due to human failures and one level due to technical failures. The technical failures are further divided on the material groups (subsystems in the aircraft) and the remaining part of the technical failures is reserved for unforeseen events.

The technical failure intensity is regarded as related to system safety and reliability, while the human failure intensity is regarded as related to test and maintenance.
6.2.3 Safety and Reliability

Safety and reliability are regarded as related to the technical failure intensity. If one looks at the test system the detection of failures is related to safety and reliability issues.

Safety and reliability requirements are managed through a System Safety & Reliability Process that is founded on MIL-STD-882C (System Safety Program Requirements), but adapted to SAAB. There are also aspects from such as MIL-STD-756B (Reliability Modelling and Prediction), MIL-HDBK-217F (Reliability Prediction of Electronic Equipment), and RTCA/DO-178B (Software Considerations in Airborne Systems and Equipment Certification) included in the process. The successor to MIL-STD-882C is less comprehensive, but contains the same basis; see MIL-STD-882D (Standard Practice for System Safety).

The purpose of the process is to identify hazardous events and initiate actions to accomplish a safe and reliable design. The process takes part in different steps of the system development concerning aircraft, crew, and interfacing environment. Examples of typical input data are customer requirements, reliability predictions, results from Failure Mode & Effect Analysis (FMEA) and Fault Tree Analysis (FTA), experience data about system, and operational data. Outputs from this process are System Safety Assessment Report, Reliability data, and final FMEA. (SAAB, 2002b)

Methodologies that are applied within the System Safety & Reliability Process are such as FMEA, Failure Mode Effect & Criticality Analysis (FMECA), Preliminary Hazard Analysis (PHA), FTA, Functional Failure Analysis (FFA), Fault Hazard Analysis (FHA), Zonal Review, and different design reviews. See, for example, MIL-STD-882C.

In the case of aircraft 39 it may be difficult to follow any template for FMEA since the system complexity is very high. However, the standard that is the foundation for the application is MIL-STD-1629A.

The vendors deliver FMEAs and FTAs for important apparatus to SAAB. The apparatus FMEAs and FTAs are used as a basis for FMEAs and FTAs on system level, performed by SAAB. However, there may be a rather big difference between apparatus level and system level, since a set of apparatus are connected in a system which results in relationships not always predicted at the time when separate apparatus are analysed. This is because concurrent work on different levels in the aircraft is important in
order to reduce the development time. The FMEAs that are constructed on
system level are used as a basis in the MSG-3 analysis.

6.2.4 Life Cycle Cost, Maintainability, and Availability
Aspects such as Life Cycle Cost, maintainability, and availability are to a
large extent managed through an Integrated Logistic Support Process,
where the support system is designed. Examples of aspects that are covered
are Life Support Cost analysis, maintenance requirements on BIT, and
MSG-3 analysis.

The MSG-3 (Maintenance Steering Group 3) analysis is adapted to SAAB.
The name MSG-3 is applied within the aerospace industry while outside it
the methodology is known as Reliability-Centred Maintenance (RCM). The
aim of the maintenance need analysis is to design the preventive
maintenance from a technical and economic point of view, at the same time
as airworthiness is secured. The analysis is performed in cross-functional
teams, where knowledge about areas such as design, system safety, the
specific technical system, test, maintenance, and customer support are
represented. As a basis for the analysis System/Subsystem Specification
(SSS) and system FMEA are used. The output from the process is
schematics, diagrams, and a task summary. The purpose of the schematics
and diagrams is to picture the functional description of the Maintenance
Significant Item (MSI), through component location and function. The task
summary is intended to provide a total picture of the preventive
maintenance for the analysed MSI. (SAAB, 2001)

Methodologies that are used in the MSG-3 analysis are identification of
Maintenance Significant Items (MSI), Failure Mode & Effect Analysis
(FMEA), and MSG-3 analysis. Tools that are applied are, for example,
FMEA-sheets, and the MSG-3 Decision Tree Diagram. See Nowlan & Heap

MSG-3 indicates what kind of maintenance is needed, time between
inspections, and so forth. As one example, failures that are classified as
hidden require shorter test intervals than failures that are classified as
evident.

6.3 Health Management
The application of Health Management that has been studied is related to
methodologies and tools of the approach that have been implemented on-
board aircraft 39. However, the purely technological solution is not in
focus, but rather the function of the methodologies and tools. The tools of
Health Management are in the case of aircraft 39 technological solutions that are built into the aircraft. The methodologies that are included in aircraft 39 are Functional Monitoring (FM), Redundancy Management (RM), and Built In Test (BIT). Furthermore BIT encompasses the three methodologies Safety Check (SC), Functional Check (FC), and Fault Localisation (FL), see Figure 6.4. A more thorough description of the methodologies will be described later in this chapter.

Aircraft level Functional Monitoring, Reconfiguration & Built In Test (FM/RM & BIT), are technological solutions built in equipment on-board the aircraft. The aircraft level test is a complement to the workshop level test. There is also an aircraft level Maintenance Data Recording System in the aircraft, which in combination with a Maintenance Ground Support System is intended to assist in system follow-up and in complicated fault localisation. (FMV, 2001b)

Built In Test (BIT) refers to functions that are intended to test systems on-board the aircraft. The purpose of BIT is to verify the function and performance of systems or some equipment within the electrical system, and to support the localisation of faults. (FMV, 2001b)

<table>
<thead>
<tr>
<th>WHAT</th>
<th>Functional Monitoring (FM)</th>
<th>Redundancy Management (RM)</th>
<th>Built In Test (BIT)</th>
<th>Fault Localisation (FL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Functional Monitoring (FM)</td>
<td>Redundancy Management (RM)</td>
<td>Built In Test (BIT)</td>
<td>Fault Localisation (FL)</td>
</tr>
<tr>
<td></td>
<td>During Normal Operation</td>
<td>During Normal Operation</td>
<td>Safety Check (SC)</td>
<td>During Normal Operation</td>
</tr>
<tr>
<td></td>
<td>During Normal Operation</td>
<td>When System is Powered Up</td>
<td>Functional Check (FC)</td>
<td>After Maintenance</td>
</tr>
<tr>
<td></td>
<td>Change Operating Mode</td>
<td>Detect Faults and in Order to Achieve Safety Requirements or Mission Success</td>
<td>To Verify Function After Performed Maintenance</td>
<td>After FM/RM, SC, or FC has Detected a Failure or a Fault</td>
</tr>
<tr>
<td></td>
<td>Detect Failure or Fault and Inform the Pilot</td>
<td>Change Operating Mode</td>
<td>Built In Test (BIT)</td>
<td>Fault Localisation (FL)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.4 Aircraft level Health Management methodologies that are included in aircraft 39, when the methodologies apply and why they exist.

6.3.1 Design of Aircraft Level Health Management
SAAB has a process for the design of Functional Monitoring, Redundancy Management & Built In Test (FM/RM & BIT) for subsystems in aircraft 39. This design process is performed in parallel with the System Safety &
Reliability Process and the Integrated Logistic Support Process. Hence, close cooperation between participants in the three processes is necessary, since the activities in them are concurrent and each one affects the others. See SAAB (2003).

The direct requirements on FM/RM & BIT on subsystem level are derived from sources such as the following (SAAB, 2003):

- Customer requirements through the Product Specification on applicable subsystems, such as:
  - Subsystem specific requirements.
  - Indirect requirements through availability and maintenance requirements.
- Company standard requirements.
- Interfacing requirements from:
  - Neighbouring subsystems.
  - Central functional monitoring.
  - Central test function.
  - Display and control system
  - Data registration system

Interfacing requirements on a system are documented in an Interface Requirements Specification (IRS), where requirements from interfacing systems are listed. The interface does not necessarily have to be mechanical, but may be such as heat interchange, electrical or discrete signals, bus signals, and hydraulic power.

Examples of system safety requirements that are deployed down to FM/RM & BIT on subsystem level are (SAAB, 2003):

- The subsystem’s budget of “probability of loss of aircraft”.
- The maximum allowed probability for certain events, based on a PHA on aircraft level.
- Safety critical functions, which are connected to catastrophic and critical events in accordance with MIL-STD-882C, with the additional division into “evident” and “hidden” failures in accordance with MSG-3.
- A classification of specific hardware and software components in accordance with the combination of criteria given in MIL-STD-882C, MSG-3, and RTCA/DO-178B.
Examples of maintenance and availability requirements that are deployed down to subsystem level, in order to design FM/RM & BIT, are (SAAB, 2003):

- Limitations in test time.
- Requirements on availability.
- Maximum Mean Time Between Failures (MTBF) and Mean Time Between Replacements (MTBR), which will affect if and how a specific component needs to be tested.
- Maintenance intervals.
- False alarm rate.
- Failure detection probability.
- Fault localisation probability.
- Operator interaction requirements and use of external equipment related to maintenance intervals.
- Allowed maintenance time per flight hour.

Examples of other requirements that have to be stated, in order to design FM/RM & BIT are (SAAB, 2003):

- A definition of possible modes required for the test system to operate in, or to reconfigure to, when a failure occurs.
- Identification of subsystem functions that may affect mission success.

### 6.3.2 Aircraft Level Health Management

Aircraft level FM/RM & BIT depends to a large extent on test and monitoring functions that are built into the hardware and software of different systems in the aircraft. In some cases additional external equipment is necessary. (FMV, 2001b)

The BIT is made up of tests of the electronic system and such tests of systems that are performed in cooperation with the electronic systems. No additional equipment for test functions is included in the aircraft. The test functions are mainly included in the systems' software. The coordination of different tests is made by the main computer. The BIT tests complete systems in the aircraft, in order to verify the systems' functions and performance (preventive actions), and to be an aid in the correction of failures. (FMV, 1999)

Central on-board software (in the main computer) initiate, coordinate, and controls the tests of different aircraft systems in cooperation with decentralised software, in the respective system. The central software also
summarises the test results of the system tests and controls the communication, i.e. the presentation and manoeuvring, between the operator (pilot and technician) and the BIT. (FMV, 2001b)

Aircraft 39 has been developed so as to be easy to maintain and to prepare for flight. The BIT has great capability to discover failures and to be a valuable aid in, for instance, fault localisation. The BIT can normally detect failures down to line-replaceable unit (LRU) without any assistance of any external test equipment. The BIT will also verify that correct function is available before mission execution. The tests and preparation before mission can be made without the aid of any ground-based power-source. The aircraft has an Auxiliary Power Unit (APU) that makes electric and hydraulic power available under all circumstances. The design of the aircraft has minimised the need for equipment and manpower. Ground-based equipment that is needed can easily be transported between different areas, if necessary. (FMV, 1999)

To fulfil the requirements for flight safety the systems of the aircraft are designed with redundancies for critical equipment, functions in equipment, supply, and so on. To be able to utilize the redundancies there is a combination of Functional Monitoring (FM) and Redundancy Management (RM). When a failure is detected by the FM there is an alarm presentation, and an automatic backup system manages a controlled degradation of the aircraft, i.e. through RM. To discover failures before a mission is started the aircraft performs a Safety Check (SC) before take-off, at power up. The SC is to verify that the aircraft systems are intact before a mission. The SC is automatic and is performed by the BIT in the respective aircraft system. (FMV, 1999)

To meet the requirements on tactical persistence the aircraft systems are constructed with a common built-in persistence in the functions and their cooperation, i.e. through RM. The persistence is partly achieved by successive degradation to lower functional levels, and partly by the utilisation of alternative signal sources or signal paths, but also with redundancies. (FMV, 1999)

Depending on how often the tests have to be performed they are divided into two main functions (FMV, 2001b):

- **Safety Check (SC)** is a test that starts automatically at start of the aircraft and that follows the whole power up sequence. Some parts of the SC can also be initiated and repeated manually when needed. The SC is
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primarily directed towards the pilot’s need to verify the functions of the aircraft, but it also covers an essential part of the requirements for preventive maintenance. At power up of the aircraft a vast number of tests that are included in the SC are performed. The tests are made up of the built in tests, internal SC, that are included in different systems and that are administrated by centralised software for the SC. The purpose of the tests is to improve flight safety, tactical safety, mission success, and to facilitate possible fault localisation. The SC can be initiated manually for one system at a time. A manually initiated SC is normally not as comprehensive as an automatically initiated SC.

- **Functional Check (FC)** covers the tests that are required, in addition to the SC, for the preventive maintenance at different intervals, for verification of remarks, for check after installation of apparatus, and for supervision. In some cases external equipment may be necessary in order to perform the FC. The FC can only be performed for one system at a time. FC also includes some tests that aid in Fault Localisation (FL) (FMV, 2001a).

### 6.3.3 Subsystem Level Health Management

Most of the aircraft systems have built-in test. These tests are divided into internal FM and internal SC. Internal FM monitors the system as long as it is under voltage. Internal SC constitutes of software functions that are partly initiated automatically, at voltage or by central SC functions, and partly manually by operator. In addition to the central test function there are also a number of independent tests. (FMV, 2001b)

### 6.4 Stakeholder System

The health data and information that are received through the test system at aircraft level are answers to different stakeholder requirements. Some of these stakeholders and their requirements on health data and information are described in this section.

One of the functions of the main computer is to register data for flight safety, maintenance, and system loss (FMV, 1999). As a basis for maintenance actions a number of reports, which include information such as operational statistics and detected failures, are summarised (FMV, 1999). The maintenance data and information are primarily directed towards technicians at different maintenance levels.

The Swedish aerospace industry, the Swedish Defence Materiel Administration (FMV) and the Swedish Air Force have a long tradition of cooperating in the monitoring and collecting of operational data. This has made it possible to detect trends in the operational performance at an early
stage and to work with continuous improvement of both the aircraft and the support system. (Sandberg & Strömberg, 1999)

Operational data is collected by the Air Force and stored in an information system. The industry has access to the operational data online, via links to some parts of the information system. Examples of data are flight hour production, field occurrences, and performed maintenance actions, both preventive and corrective. The data is used to continuously monitor the operational performance of both the aircraft and the support system. The test system is used extensively in the evaluation of occurrences. Some field occurrences require immediate corrective action. However, in most cases alternative solutions with different implications to the aircraft and the support system are possible. A solution may be anything from the update of a technical instruction to the modification of hardware in the aircraft. The consequences for both system performance and cost may differ quite a lot depending on the extent of the proposed change. Each change to either the aircraft or the support system must be evaluated in order to make sure that it contributes to the effectiveness of the total system in a cost effective way. This work with continuous improvements of the aircraft and the support system requires a constant interaction between operation and development. (Sandberg & Strömberg, 1999)

Examples of experience data that are followed-up are material failures, logistics support times and spares consumption. In order to evaluate how the actual performance and support costs meet originally stated requirements on system level a system evaluation report is compiled every year. In the evaluation report actual experienced data is compared to predicted values of system performance. The difference between predicted and actual values is analysed and consequences identified. Based on the differences and their consequences proposals for changes of the aircraft and the support system are formulated and evaluated. Some examples of changes that may be suggested, in order to improve availability performance or Life Support Cost (LSC) may be modifications of the aircraft, changes in maintenance procedures, or even in the maintenance organisation. (Sandberg & Strömberg, 1999)

6.4.1 Operators
The operators of the aircraft may be seen as the pilot and the technician, but if the system boundaries of the joint system are extended the Air Force may also be seen as operators of the aircraft.
The close integration between different subsystems in the aircraft enables a simultaneous analysis of different data in order to present optimised information to the operator. This optimised information may be based on data and information such as flight data, armoury, tactical information, and so on. The electronic system is divided into a number of functional areas. The main computer also has functions for superior control of the test system. (FMV, 1999)

Central software cooperates with decentralised software to initiate, coordinate, and control the tests. The central software also summarises the test results and controls the communication between the operator (pilot or technician) and the BIT. The presentation is made through the following evaluation functions (FMV, 2001b):

- **A Fast Report** presents, after a completed mission, the functional state of the aircraft, with regard to failures and events that have occurred and been detected. This report is mainly directed towards the pilot.

- **Fault Localisation** (FL) analyses data that has been stored during the SC and locates the failure to a faulty line-replaceable unit (LRU). FL acts as assistance in the localisation of faults discovered by the SC or FC. If the SC for any subsystem discovers something that may be critical to flight safety, interfere with missions, or require a remark, an automatic FL is performed. The data that has been registered during the SC is analysed and the first suggestion of action that FL finds for the subsystem is registered in a database for maintenance and flight safety. The presentation of FL is selected and initiated manually for any optional subsystem, based on the summarisation of the SC. During FL the registered data from the SC is analysed and discovered faults are located to a LRU or group of LRUs. In some cases the FL recommends further actions, e.g. that another test or a manual FL should be performed. If the information from the SC is not satisfactory some additional BITs may have to be necessary to be performed. These additional tests are included in the FC and are coordinated with the other tests within FC.

- **A Failure Report** presents located faulty LRU based on data about failures in different aircraft systems that have been discovered during operation. After a completed mission the function gives information about discovered failures, the condition of flight at the failure event, and appropriate maintenance action.

- **A Modification Status Report** presents the edition of different units in the aircraft that have been stored during the SC. The configuration of the aircraft, i.e. the actual combination of included equipment, is checked on the basis of information about the aircraft’s identity and modification
status. If the configuration is not allowed this is classified as a flight critical failure and an alarm is given.

In addition to the reports the communication with the operator can be made through a number of alarms. The alarms are given at a number of failures, or when a test has not been performed within stated time limits. The alarms are connected to three different failure levels, namely (FMV, 2001a):

- Flight critical failures, which means that an obstacle to flying has occurred.
- Failures that interfere with mission, which may interfere with some types of missions or may not even require an immediate action. The failure can be handled by the pilot when s/he is aware of it.
- Failures that only give a remark and do not require any immediate action and any alarm via the FM.

Pilot
During mission the pilot wants to know three things, namely, failure, action, and consequence. The pilot wants to know what has failed and where, but not on the component level. The pilot also wants to know what to do at failure, for example fly carefully, or at low altitude.

It is important to distinguish between primary failure and secondary failure. Primary failures may, however, lead to secondary failures that are more critical than the primary failures, and in these cases the failures that are most critical should be presented to the pilot.

It is important that the information is directed to the pilot and not designed in accordance with the needs of the technician, who wants information on a more detailed level.

The alarms should also differ with regard to the criticality of the failure. It would also be preferable for the pilot if the alarms could be suppressed so that they are presented to the pilot at a convenient time.

The alarms are today presented in priority order. The alarm that is presented first requires immediate action, while the second alarm indicates that the pilot should end the mission and return to the base. The third level of alarms only gives information that a failure has occurred, but no action is required by the pilot.
CASE DESCRIPTION

The pilot does not want any false alarms, and do want unambiguous information that does not need any complementary information.

After a completed mission the pilot is interested in reviewing the information that has been presented, in order to evaluate the mission. As one example, it is not certain that the pilot has registered all information that has been presented.

There is a registration aimed at tactical, surveillance, and training requirements. Sensor data, communication, and presentation and signals from radar, homing device, and camera are recorded. It is possible to replay recordings and present them via the ordinary on-board displays, or with the aid of ground-based evaluation-equipment. (FMV, 1999)

Technician

The technicians are the primary users of a test system. Today there are two different levels for maintenance of aircraft 39. The B-level has been excluded, but existed in the original design of the support system:

- **A-level.** The maintenance is performed at the squadron at an Air wing from aircraft level down to LRU level. Maintenance includes such measures as turn-around services, some minor inspections, fault localisation down to LRU, and the replacement of faulty LRUs. Suggestions for appropriate actions that the test system gives to the technician are based on time for change and probability of failure for the LRU or apparatus. The technician on A-level wants to know what LRU to change in the aircraft.

- **B-level.** The preventive maintenance is performed at the Air Force, in the form of more thorough inspections than on A-level. Preventive and corrective maintenance of simple LRUs that are removed from the aircraft. Also some structural inspection and repair may be performed on this intermediate level.

- **C-level.** More thorough inspections than on the other levels are performed. Complex LRUs are repaired and overhauled. C-level maintenance is mainly performed at the developing organisations, but also at two air wings of the Air Force. Technicians on C-level want data and information on apparatus level for fault localisation, and also statistics on apparatus level. On the C-level it is important with a fault localisation that is as exact as possible, in order to correct the fault easily.

The technician uses the test system for Fault Localisation and safety critical failures, which should be correct and trustworthy. The technician wants
fault localisation that is unambiguous, stable, and credible. Everything that has been presented to the pilot should be possible to reconstruct. It may also be beneficial for the technician to be able to receive the same information as the pilot, in order to locate possible causes of failures. The technician wants exact fault localisation of LRU. For the technicians it is preferable to exclude manual fault localisation in the technical system.

**Planners**
There are mainly two types of planners. These are mission planners and maintenance planners.

The mission planners state requirements on the squadron, which in turn plans the maintenance with regard to mission requirements.

The maintenance planners want failures to be corrected in a short time, since the time factor is crucial, which puts requirements on fault localisation. The maintenance planners want data and information in order to be able to plan the maintenance. Based on the data and information from the test system it may be possible to coordinate maintenance that has to be performed and such maintenance that does not necessarily have to be performed at the moment, but may be beneficial to perform at the same time as the maintenance that must be performed. This judgement is based on a combination of actual data and information and historical experiences.

It is preferable that failures that are safety critical are discovered before take-off, in order to save time and money. This is also the purpose of the Safety Check.

**6.4.2 Developers**
Developers of the aircraft are the industries that design and build systems in the aircraft, and that also design the support system. In the case of aircraft 39 are the developers are IG JAS and BAE SYSTEMS.

The designers want data and information in order to enable an improvement of the design. The integrated logistic support also wants information.

SAAB wants statistics on aircraft level. SAAB uses the data and information in order to see how reliable the systems are and for development and improvements of the systems. SAAB supervises failures and causes. A report that contains an analysis of the failures is delivered to the representative of the customer, FMV, every year.
Volvo collects data from the engine in order to develop it and perform maintenance. Ericsson uses health data and information in order to see how reliable the systems are and for development and improvements of the systems.

**Flight Safety Investigators**
In case of system loss data can be retrieved from a special memory that is constructed to withstand an aircraft crash (FMV, 1999). This registration is primarily directed towards the needs of flight safety investigators, in the case of an accident.

**6.4.3 Customer**
The customer of the aircraft is represented by the Swedish Defence Material Administration (FMV). Safety requirements are connected to Safety Check and Functional Monitoring, which may be found in the Product Specification that has been agreed upon between SAAB and FMV. Requirements on costs are stated by FMV, which represents the customer, and the Air Force, which is the user. The Product Specification also gives requirements on reliability for systems and subsystems. According to the Product Specification, that states customer requirements, critical functions should be covered by Functional Monitoring.

**6.4.4 Some Thoughts about Requirements on Health Management**
There are mainly three overarching requirements on a test system. These requirements are flight safety critical conditions, in accordance with Rules for Military Aviation (RML), availability performance, and fault localisation. Safety, reliability, costs, and availability are requirements on the design of the test system. The most important requirement is safety, which in turn affects the dependability and cost. Reliability requirements are in wartime related to mission probability and repair times. The costs are on man-hour and material not the system.

Redundant functions are more difficult to monitor than active functions. The test of redundant functions may be made during power up of the aircraft, that is, during the Safety Check. It may be the case that functions are tested because they are safety critical and because it is possible to test them.

It is important that Functional Monitoring covers primary functions and not secondary functions. It is also important to point out primary failures and not secondary failures.
It is important to design the construction of alarms thoroughly. There are fewer alarms than failures, since several failures may be combined into one alarm. It is desirable to combine failures that are not critical individually, but that together may be critical. It is also preferable to be able to extend a test system when it turns out that unforeseen failures are present.

The Safety Check should only cover functions that need to be covered, not everything that is possible to test. It may also be necessary to review earlier decisions about what functions to cover in order to reduce unnecessary functions, which most probably will only result in false alarms, and also to be able to include functions that were perhaps not predicted to be of importance. There may emerge new requirements on the test system with new users, since it is difficult to predict every possible requirement in the original design of the test system.

There are some things that a pilot takes into consideration when interrupting a mission, but that the test system does not discover, such as certain kinds of vibrations. One challenge in the design of test systems for Unmanned Aerial Vehicles (UAVs) is to solve this kind of human sensing.

Both the technician and the pilot want the information from the test system to be exact and not possible to misinterpret.

Requirements on Fault Localisation are that it not should interfere with mission and that it should decrease the maintenance cost.

False Alarms
The reliability of sensors must be very high in order to avoid false alarms. It is also important with good tolerances in the tests, in order to avoid false alarms. The operational environment can affect the false alarm rate, since a cold climate may result in different valves having longer opening times than in a warm climate, which may affect test results. That is, a failure alarm can be given, even though a failure is not really present.

One risk with false alarms is that they may lead to mistrust to the test system, which may lead to that real failures are ignored, which in turn may have dangerous consequences. However, in the case of aircraft the risk for false alarms is low, compared with products such as cars, since no unnecessary risks are taken.
CASE DESCRIPTION

There are also costs connected to false alarms. These costs are due to such things as interrupted missions and extended time for fault localisation. There may be unnecessary transportation of apparatus between operation and workshop level when there are false alarms. The time for fault localisation may be rather extensive because a LRU may be removed from the aircraft on A-level and sent to C-level for a more extensive fault localisation. This may result in the LRU coming back with no action taken, but at the same time both time and resources have been spent on the localisation of faults that do not exist. However, the safety consciousness is high and no unnecessary risks are taken, and therefore is it very important to avoid false alarms. Maintenance requirements on a system may have to include false alarms in order to highlight the importance of avoiding false alarms.
PART III: THE CONCLUSION

CHAPTER 7: ANALYSIS AND RESULTS
In this chapter the combined analysis of the theoretical and empirical findings, and the results of this analysis, will be presented. First the analysis of theoretical findings into a framework for continuous improvements will be presented. Thereafter, some identified processes from the case study will be outlined. The processes will then be conceptualised into a combination of methodologies that supports the work with continuous improvements. Thereafter, some suggestions of supporting tools will be presented. Finally, some suggestions for combination and adaptation of some methodologies and tools will be described in a holistic model for continuous improvements of complex technical systems.

CHAPTER 8: CONCLUSIONS AND DISCUSSION
The discussion in this concluding chapter will summarise some major conclusions that may be drawn from this study. The areas of discussion will be centred on the stated research purpose and research questions of the study. Finally, some aspects about reliability, validity, and further research will be discussed.
7 ANALYSIS AND RESULTS

In this chapter the combined analysis of the theoretical and empirical findings, and the results of this analysis, will be presented. First the analysis of theoretical findings into a framework for continuous improvements will be presented. Thereafter, some identified processes from the case study will be outlined. The processes will then be conceptualised into a combination of methodologies that supports the work with continuous improvements. Thereafter, some suggestions of supporting tools will be presented. Finally, some suggestions for combination and adaptation of some methodologies and tools will be described in a holistic model for continuous improvements of complex technical systems.

7.1 Analysis Foundation

A central theme of the performed analysis is the management system view presented by Hellsten & Klefsjö (2000) and Akersten & Klefsjö (2003). This management system view may hence be applied in order to illustrate the order of analysis applied in this thesis. The analysis starts at the core values, and identifies, combines, and adapts supporting methodologies. Finally, some supporting tools are identified, combined, and adapted. This way of thinking is conceptually described by Hellsten & Klefsjö (2000). A more pragmatic description of the approach related to Dependability Management is made in Akersten & Klefsjö (2003), by an adaptation of the Matrix Diagram. However, the present writer has chosen to apply some additional tools from the Seven Management Tools, as described by Mizuno (1988). The reason for this choice is the initial emphasis on the exploration of the studied area. The results of the exploration and analysis are different descriptions of the area that are founded on the mapping and structuring of qualitative data.

7.2 Framework for Continuous Improvements

The findings of the initial literature study were analysed through a theoretical perspective based on the management system view presented by Hellsten & Klefsjö (2000) and Akersten & Klefsjö (2003). The system view was applied in order to group the literature findings into the two system elements of methodologies and tools. To support this work the Affinity Diagram, as described by Mizuno (1988), was used as a supporting tool. In order to get a more specific relationship between different elements within each management approach theories within each approach were used. In order to support this work the Relations Diagram tool, as described by Mizuno (1988), was applied. The mapping of Requirements
Management and Health Management may be found in Chapter 3 (Perspectives on Presented Theories). This analysis was mainly made by the author over an extended time period. However, the present writer had continuous conversations with both colleagues at the university and persons in the project group in the participating industrial organisation. The mapping and structuring of Health Management is presented in Paper A (Aerospace Diagnostics and Prognostics in a TQM-Perspective).

In order to combine the three management approaches the management system view of Quality Management, and some of its core values were applied. In this way the core values acted as a link between the three approaches. The knowledge about included methodologies and tools in each approach, which was gained in the previous step of the analysis, also supported the work with relating the three approaches to each other. To support this work the rationale of the Relation Diagram (Mizuno, 1988) was applied. Once again the analysis was mainly made by the author over an extended time period with continuous communication with both colleagues and persons within the project group. This analysis resulted in a management framework, where stakeholder requirements and system functions are central. This framework is presented in Chapter 3 (Perspectives on Presented Theories) and represented in Figure 7.1.

On a conceptual level this management framework indicates how an organisation can work with continuous improvements of functions related to complex technical systems. A further discussion of the management framework may be found in Chapter 3 (Perspectives on Presented Theories). This result is presented in Paper B (Continuous Improvements of Complex Technical Systems: A Theoretical Quality Management Framework Supported by Requirements Management and Health Management).
7.3 Processes for Continuous Improvements

The analysis of identified processes in the case study was based on the management system view of Quality Management and the constructed management framework. The focus of the analysis was on processes that included methodologies and tools for the management of stakeholder requirements and system functions, and how these were interrelated. The analysis was mainly performed by the author, with support from persons in the project group in the participating industrial organisation. When additional support was needed different persons were identified and interviewed in order to facilitate the analysis.

The identified processes may be summarised in the three processes Product Development, Integrated Logistics Support, and System Safety & Reliability, see Chapter 6 (Case Description). The product development process includes the design of both the technical system and the support system. This approach is natural since the stakeholders external to the developing organisation are interested in the functions of the product (the combination of the technical system and the support system) and less
interested in where the functions are realised. However, in this thesis the focus is on the technical system and its functions, and the elements of the support system are seen as stakeholders of the technical system. The interface between the technical system and the support system is manifested by health data and information received from the part of the technical system that is related to Health Management. This part of the technical system consists of the methodologies Condition Monitoring, Diagnostics & Prognostics, and supporting tools such as sensors and Artificial Intelligence, see Chapter 3 (Perspectives on Presented Theories) and Chapter 6 (Case Description). Hence, the three integrated processes may be seen as one Technical System Development Process, one Integrated Logistics Support Process, and one System Safety & Reliability Process. The input to the processes is stakeholder requirements and the output from the processes is critical functions that should be covered by tools from Health Management. See Figure 7.2.

**Figure 7.2** Three interrelated processes that support the work with continuous improvements by providing traceability between stakeholder requirements and system functions that should be covered by tools from Health Management. From Söderholm (2003b).

### 7.4 Methodologies and Tools for Continuous Improvements

Within the three management approaches included in the management framework and the three identified processes a number of methodologies exist. The selection and combination of appropriate methodologies were mainly based on the core values in Quality Management that were in focus
in the study, see Chapter 3 (Perspectives on Presented Theories). However, an awareness of other core values of Quality Management also contributed to the selection of appropriate methodologies. The four fundamental core values that the methodologies should support were Continuous Improvements, Stakeholder Focus, Fact Based Decisions, and System View, which was indicated by the initial literature study. Other core values that were also considered were Everybody’s Participation and Process View, which are described in the literature (see Chapter 2: Theoretical Frame of Reference) and that emerged as important also in the case study.

The model is mainly founded on ideas and aspects of four existing and widely, often successfully, applied methodologies. These methodologies are Quality Function Deployment (QFD), Failure Mode & Effect Analysis (FMEA), Reliability-Centred Maintenance (RCM), and Safety & Reliability Analysis (SRA) founded on the description in MIL-STD-882C. One main reason for this selection is that the methodologies emphasise either stakeholder requirements or system functions, even though the other aspect always is present in some way, for example as decision criteria. See Figure 7.3.

![Figure 7.3](image)

Figure 7.3 The interrelationship between some methodologies that are related to each other in order to enable traceability between stakeholder requirements and system functions. From Söderholm (2003b).

The proposed combination of methodologies is intended to enable traceability between stakeholder requirements and system functions. This traceability is seen as the key to successful work with continuous improvements of complex technical systems. The reason for this is that the
effects and consequences of proposed changes can be “predicted” through
the application of the proposed methodology in the “requirements
domain”. The prediction can later on be verified through the collection of
health data and information, which should reflect system functions that
 correspond to stakeholder requirements in the “functions domain”. Proposed changes may also originate in the evaluation of monitored
functions, if it is discovered that the requirements of stakeholders are not
fulfilled, through diagnostics or prognostics activities.

The perspective in QFD is founded on the stakeholder view and sets out to
transfer these into corresponding system functions. FMEA, RCM, and SRA
have a perspective influenced by the prevention or reduction of failure of
system functions, which is identified through stakeholder requirements.
The combination of aspects from the four mentioned methodologies above
should enable a strong connection between stakeholder requirements and
system functions. The choice of the word “requirement” or “function” is
more due to whether the perspective originates from the stakeholders or
the system. Another common strength in the methodologies is the
combination of both a systemic and a systematic approach.

The reason for selecting RCM and the specific SRA, was mainly based on
findings in the case study. These two methodologies are common in the
aerospace industry all over the world, and have also proved to be
successful. Here it should be noticed that RCM is called MSG-3
(Maintenance Steering Group 3) in the aerospace industry and RCM
outside the aerospace industry. RCM mainly focuses on maintenance
issues, while the SRA mainly focuses on safety and reliability aspects, even
though they partly cover each other also in these aspects. The literature
study also corroborated these empirical findings. In both these
methodologies FMEA may be applied. However, even if the stakeholder
requirements are the foundation for the work with the three methodologies
mentioned above, the focus is on system functions. In order to emphasise
more strongly the aspect of stakeholder requirements some additional
methodology seems necessary to be included. According to Macaulay
(1996), QFD is a common methodology when a Quality Management
approach is adapted to the management of stakeholder requirements. The
idea of combining QFD, FMEA, and Fault Tree Analysis (FTA) is described
also by Akao (1992), who applies the latter two for “reliability
deployment”.

Stamatis (1995, pp. 65-69) describes how QFD and FMEA complement each
other. Both methodologies aim at continuous improvements, stakeholder
satisfaction, and the reduction of failures. However, they cannot replace each other since QFD gives input to the FMEA.

Many descriptions of RCM emphasise the fundamental importance of FMEA. For instance, Nowlan & Heap (1978) state that the FMEA-sheet can be used in combination with operator experiences in order to identify functions which are necessary to analyse further. Moubray (1997) also describes the importance of the result of the FMEA as input to the RCM Decision Diagram.

In MIL-STD-1629A (p. iii) it is stated that although the FMEA is an essential reliability task, it also provides information for other purposes. Some situations that are regarded as appropriate for the FMEA are maintainability considerations, safety analysis, logistics support analysis, and the design of subsystems for failure detection and isolation. One example of where the FMEA is mentioned as an appropriate support, in order to determine the optimal design of an on-board level BIT, is MIL-STD-1591.

In the references above the importance of the FMEA and its connection to the three other methodologies may be seen. Therefore, the FMEA is considered as a central methodology that connects and summarises information from the other three methodologies. See Figure 7.3.

### 7.4.1 Quality Function Deployment

Akao (1992) describes QFD as a methodology that ensures quality throughout each stage of the product development process, starting with design. The aim of QFD is to satisfy the stakeholders by transferring the requirements of the stakeholders into design targets and major quality assurance measures to be used throughout the production stage (Akao, 1992).

Slabey (1990) states that QFD translates stakeholder requirements into appropriate organisational requirements at each stage from research and product development through engineering and manufacturing and marketing, sales, and distribution.

Bergman & Klefsjö (2003) state that QFD is an excellent methodology for supporting communication and participation, and accordingly the core value Everybody’s Participation. This is because QFD requires cross-functional teams to meet and work out common concepts, and it provides a common basis necessary for integrated product development.
Experiences have shown that QFD has reduced by half the problems previously encountered at the initial stages of product development and has reduced development time by one-half to one-third, while also ensuring stakeholder satisfaction and increasing sales. However, if QFD is applied incorrectly it may increase work without achieving the potential benefits. (Akao, 1992)

The central tool that QFD is founded on is different versions of the Matrix Diagram, of which the House of Quality probably is the best-known (Akao, 1992). Other tools that may be a support in the work with requirements are standards such as IEEE STD 610.12, ANSI/IEEE STD 830, and IEEE STD 830.

The Matrix Diagrams of QFD is adapted to the purpose of this study. The result of the adaptation is three successive diagrams. The first diagram shows the correlation within stakeholders, the correlation within requirements, and the relationship between stakeholders and requirements. The second diagram shows the correlation within stakeholder requirements, the correlation within system functions, and the relationship between stakeholder requirements and system functions. The third diagram shows the relationship between system functions and subsystem functions, and the correlation within each set of functions. See Söderholm (2003b).

7.4.2 Failure Mode & Effect Analysis

Failure Mode & Effect Analysis is a very useful methodology for reliability analysis. Some examples of applications of FMEA are rough qualitative analyses initiated during planning and design, a more detailed and quantitative analysis during design and development, and for pre-production engineering. (Bergman & Klefsjö, 2003)

The FMEA is an engineering methodology that is applied in order to define, identify, and eliminate known and potential deviations from a process or a product before they reach the stakeholders. Hence the aim of FMEA is to maximise the satisfaction of the stakeholders by eliminating and reducing known or potential deviations. The FMEA is alive, updated continually, and never really completed. Hence, FMEA is a true dynamic methodology for continuous improvements. (Stamatis, 1995)

The FMEA should be initiated as an integral part of the early design of a system and should be updated to reflect design changes. FMEA should also
be a major consideration at each design review, from the first preliminary one to the final design. Hence, the FMEA must be iterative and reflect the design process. If the work is appropriately performed it can be useful and effective in order to supporting and improving both system design and decision making. (MIL-STD-1629A)

The FMEA is a methodology that requires a cross-functional and multidisciplinary team. The FMEA cannot be done on an individual basis. The team must be defined as appropriate for a specific situation and cannot serve as a universal FMEA team in an organisation. (Stamatis, 1995)

The FMEA should start as soon as possible, even when all the facts and information are not known. The FMEA starts when a new process or product is designed, when a new application is found for the process or product, and when improvements are considered for an existing process or product. (Stamatis, 1995)

Any FMEA conducted properly and appropriately will provide the practitioner with useful information that may reduce the risk and work load related to the unit of analysis. This is because the FMEA is a logical and progressive potential failure methodology that allows the task to be performed more effectively. (Stamatis, 1995)

The methodology of FMEA is in many studied sources considered synonymous with the FMEA-sheet. However, in this thesis the FMEA-sheet is seen as a supporting tool of the FMEA, which is a methodology. Another tool that supports this work is MIL-STD-1629A.

The FMEA-sheet is a central tool in all the selected methodologies that are identified and combined in the analysis. However, the FMEA and the FMEA-sheet have by the present writer been extended and adapted to the purpose of this study. See Söderholm (2003b).

7.4.3 Reliability-Centred Maintenance

Reliability-Centred Maintenance is a methodology for the development of scheduled maintenance, with the aim of realising inherent reliability capabilities of the system at minimum cost. The resulting scheduled maintenance includes all tasks necessary to protect safety and operating reliability, and only the tasks that will accomplish this objective. (Nowlan & Heap, 1978)
The system is partitioned in order to identify Maintenance Significant Items (MSIs). In order to support this work a Decision Diagram that resembles of a tree-diagram is applied as a supporting tool. See Nowlan & Heap (1978).

The decision diagram logic is also applied in order to decide if the maintenance task is cost-effective. The cost-effectiveness is only considered for maintenance tasks that are related to uncritical failures. In this case aspects such as failure-rate, operational consequences, unusual high repair or operating costs are considered. The logic for the Decision Diagram is also useful in order to decide upon feasible product improvements. (Nowlan & Heap, 1978)

Some benefits that may be achieved with RCM are (Moubray, 1997):

- Greater safety and environmental integrity.
- Improved operating performance.
- Greater maintenance cost-effectiveness.
- Longer useful life of expensive items.
- A comprehensive database.
- Greater motivation of individuals.
- Better teamwork.

The main Decision Diagram as presented by Moubray (1997) includes a number of questions that may be answered by “yes” or “no”. Every chain of answers results in a recommended task to perform in order to design the appropriate maintenance of a system. The Decision Diagram is hence applied in order to classify failures and find appropriate countermeasures for each category of failures. The first level questions cover failure consequences such as if the failure is hidden or evident, if it affects safety, has environmental implications, or interferes with operational capability, see Table 7.1. The next level of questions covers aspects of multiple failures, available technology, and economy. This level of questions is applied in order to document whether a proactive task has been selected, and if so, what type of task.
Table 7.1 Classification of functions and their failure according to Moubray (1997).

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evident or Hidden</td>
<td>Evident: A failure of the function will on its own eventually become inevitably evident to the operators under normal circumstances.</td>
</tr>
<tr>
<td></td>
<td>Hidden: A failure of the function will not become evident to the operators under normal circumstances if it occurs on its own.</td>
</tr>
<tr>
<td>Safety</td>
<td>If the failure mode results in a loss of function or other damage which may injure or kill someone.</td>
</tr>
<tr>
<td>Environment</td>
<td>If the failure mode results in a loss of function or another damage which may lead to the breach of any known environmental standard or regulation.</td>
</tr>
<tr>
<td>Operation</td>
<td>A failure of the function has a direct adverse effect on operational capability (output, quality, customer service, or operating costs in addition to the direct cost of repair).</td>
</tr>
</tbody>
</table>

The result of the RCM analysis is an appropriate action for each failure, the time intervals for the actions, and who is responsible for the action. The different types of action that may be the outcome of the RCM analysis are (Moubray, 1997):

- **Scheduled on-condition task.** A suitable on-condition task could be found to anticipate the failure in time to avoid the consequences.
- **Scheduled restoration task.** A scheduled restoration task could be found in order to prevent the failures.
- **Scheduled discard task.** A suitable scheduled restoration task could be found in order to prevent the failures.
- **Scheduled failure-finding task.** This task is only concerned with hidden failures, which by definition may result in multiple failures. The task is selected if it is possible to do the task and it is practical to do it at the required frequency, at the same time as it reduces the risk of multiple failures to an acceptable level.
- **Compulsory redesign.** The failure is serious enough to warrant redesign, due to that it affects safety or the environment.
- **No scheduled maintenance.** A deliberate decision has been taken to let failure happen, due to the fact that consequences are purely economic.
and no suitable preventive task has been found. However, in this situation the next, and last, task should be considered.

- **Redesign may be desirable.** Even though it has been decided that no preventive action is taken, redesign may be desirable.

The FMEA-sheet is a central tool for supporting RCM. Another tool is the Decision Diagram. See, for example, Nowlan & Heap (1978) and Moubray (1997). Another tool that may support the work with RCM is MIL-STD-2173(AS). For a thorough discussion about issues related to the implementation of RCM see Backlund (2003).

The Decision Diagram of RCM that seems appropriate to apply is the one described by Moubray (1997). The main rationale for this choice is the systematic inclusion of failures that could affect the environment. However, Nowlan & Heap (1978) also describe Decision Diagrams for evaluating cost-effectiveness and deciding upon reasonable product improvements.

The inclusion of failures with possible environmental effects brings the classification of failures within RCM closer to the one mentioned in MIL-STD-882C. However, the categorisation of "hidden" and "evident" failures, as emphasised in RCM adds a further dimension to the classification of failures, compared to the one in MIL-STD-882C.

### 7.4.4 Safety & Reliability Analysis

There are a vast number of different methodologies for system safety analysis and management. The one selected for the purpose of this study is the one described in MIL-STD-882C. The reason for this selection is that the standard is applied in the studied case, where it has proved to be valuable. The standard itself is seen as a supporting tool in the analysis work related to safety and reliability. Other tools that support this work are documents such as MIL-STD-756B, MIL-STD-882D, and RTCA/DO-178B. See Chapter 6 (Case Description).

System safety engineering draws upon professional knowledge and specialised skills in the mathematical, physical, and related scientific disciplines, together with the principles and methods of engineering design and analysis for specifying, predicting, and evaluating the safety of the system. The degree of safety achieved in a system is directly dependent on the emphasis given and applied during all phases of the life cycle. Safety, consistent with mission requirements, should be designed into the system in a timely and cost-effective manner. (MIL-STD-882C)
The criticality of failures is classified in MIL-STD-882C according to four categories. These categories are catastrophic, critical, marginal, or negligible. See Table 7.2.

Table 7.2 Classification of severity of function failure according to MIL-STD-882C.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>Death, system loss, or severe environmental damage.</td>
</tr>
<tr>
<td>Critical</td>
<td>Severe injury, severe occupational illness, major system or environmental damage.</td>
</tr>
<tr>
<td>Marginal</td>
<td>Minor injury, minor occupational illness, or minor system or environmental damage.</td>
</tr>
<tr>
<td>Negligible</td>
<td>Less than minor injury, occupational illness, or less than minor system or environmental damage.</td>
</tr>
</tbody>
</table>

In order to prioritise actions a matrix that combines criticality and frequency can be used. The frequencies are classified as frequent, probable, occasional, remote, or improbable, see Table 7.3. The matrix design assigns a different index to each criticality-frequency pair thus avoiding the situation caused by creating indices as products of numbers assigned to criticality and frequency. A situation where the product of criticality and frequency gives the same result hides information pertinent to prioritisation, see Table 7.4. (MIL-STD-882C)

In MIL-STD-882C an order of precedence for satisfying system safety requirements and resolving identified hazards may be found. A hazard is defined as a condition that is a prerequisite of a mishap. A mishap is, in turn, defined as an unplanned event or series of events that results in death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment. The priority order is as follows (MIL-STD-882C):

- **Design for minimum risk.** The first priority is to design in order to eliminate hazards. If an identified hazard cannot be eliminated, reduce the associated risk to an acceptable level.
- **Incorporate safety devices.** If identified hazards cannot be eliminated or their associated risk adequately reduced through design selection, that risk should be reduced to an acceptable level through the use of fixed, automatic, or other protective safety design features or devices.
ANALYSIS AND RESULTS

Provisions should be made for periodic functional checks of safety devices when applicable.

- **Provide warning devices.** When neither design nor safety devices can effectively eliminate identified hazards or adequately reduce associated risk, devices should be used to detect the condition and to produce an adequate warning signal to alert personnel of the hazard.

- **Develop procedures and training.** Where it is impractical to eliminate hazards through design selection or adequately reduce the associated risk with safety and warning devices, procedures and training should be used. This solution may not be used as the only one when the hazard is classified as catastrophic or critical.

### Table 7.3 Probability levels and their description on individual items and fleet or inventory, according to MIL-STD-882C.

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>SPECIFIC INDIVIDUAL ITEM</th>
<th>FLEET OR INVENTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td>Likely to occur frequently.</td>
<td>Continuously experienced.</td>
</tr>
<tr>
<td>Probable</td>
<td>Will occur several times in the life of an item.</td>
<td>Will occur frequently.</td>
</tr>
<tr>
<td>Occasional</td>
<td>Likely to occur some time in the life of an item.</td>
<td>Will occur several times.</td>
</tr>
<tr>
<td>Remote</td>
<td>Unlikely but possible to occur in the life of an item.</td>
<td>Unlikely but can reasonable be expected to occur.</td>
</tr>
<tr>
<td>Improbable</td>
<td>So unlikely that it may be assumed occurrence may not be experienced.</td>
<td>Unlikely to occur, but possible.</td>
</tr>
</tbody>
</table>

### Table 7.4 Example of a Risk Assessment Matrix. From MIL-STD-882C.

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catastrophic</td>
</tr>
<tr>
<td>Frequent</td>
<td>1</td>
</tr>
<tr>
<td>Probable</td>
<td>2</td>
</tr>
<tr>
<td>Occasional</td>
<td>4</td>
</tr>
<tr>
<td>Remote</td>
<td>8</td>
</tr>
<tr>
<td>Improbable</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hazard Risk Index</th>
<th>Suggested Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>6-9</td>
<td>Undesirable</td>
</tr>
<tr>
<td>10-17</td>
<td>Acceptable with review</td>
</tr>
<tr>
<td>18-20</td>
<td>Acceptable without review</td>
</tr>
</tbody>
</table>

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7.4.5 Cross-Functional Teams

Each of the four methodologies identified in the analysis emphasise the importance of cross-functional teams. This is also something that has been discovered in the case study, where emphasis on the participation of different expertise and knowledge is considered vital, due to the complexity and criticality of the technical system, see Chapter 6 (Case Description). Another discovery in the case study was that all documents had to be approved by someone else than the original author. This procedure is followed in order to secure that the documents are correct. At the same time someone else than the author of the document participates in the work. The documents are often approved by someone in a managerial position. In this way the management also has to be committed.

The identified emphasis on cross-functional teams and the procedure of approved documents support core values of Quality Management such as Management Commitment and Everybody’s Participation.

Based on the findings described above, the present writer thinks that it is most valuable to add the methodology of Cross-Functional Teams to the other four methodologies QFD, RCM, FMEA, and SRA.

7.5 Model for Continuous Improvements

The methodologies and tools that have been described in this chapter may be conceptualised in a summary holistic model for continuous improvements. However, the present writer also thinks that is necessary to include the methodologies and tools that are included in Health Management, in order to close the loop and enable continuous improvements with the aid of collected health data and information (see Chapter 3: Perspectives on Presented Theories). The methodologies and tools in Health Management may be named as in Chapter 3 (Perspectives on Presented Theories) or as in the studied case (see Chapter 6: Case Description). However, the author of this thesis selects the more common taxonomy, as suggested in Chapter 3.

It may also be beneficial to include the core values that have been the basis of the research, see Chapter 3 (Perspectives on Presented Theories), but also those identified as vital during the research. The model and its included combination of adapted methodologies and tools are presented in Paper C (A Model for Continuous Improvements of Complex Technical Systems). See also Figure 7.4.
Figure 7.4 A holistic model for continuous improvements of complex and critical technical systems. The model includes suggestions for methodologies and tools from Requirements Management and Health Management that together support the core values of Quality Management, in order to reach the aim of increased stakeholder satisfaction with a reduced amount of resources. From Söderholm (2003b).
8 CONCLUSIONS AND DISCUSSION

The discussion in this concluding chapter will summarise some major conclusions that may be drawn from this study. The areas of discussion will be centred on the stated research purpose and research questions of the study. Finally, some aspects about reliability, validity, and further research will be discussed.

8.1 Continuous Improvements of Complex Technical Systems

The purpose of this thesis is to explore and describe how an organisation can work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements, in order to increase stakeholder satisfaction with a reduced amount of resources.

In order to fulfil the stated purpose two research questions were set out to be answered:

- What kinds of methodologies and tools can support the work with stakeholder focused continuous improvements of complex technical system functions?

- How can an organisation work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements?

Both research questions were set out to be answered by the combination of a case study and a literature study, see Chapter 4 (Research Design). The first research question was set out to be partly answered by an initial explorative literature study. The study indicated that the combination of methodologies and tools in the approaches Quality Management, Requirements Management, and Health Management could strengthen and support each other and thereby systematise the improvement work. The synergism between these management approaches was illustrated in a theoretical management framework made by the author. This framework gives a holistic view of how an organisation can work with continuous improvements, see Chapter 3 (Perspectives on Presented Theories), which addresses the second research question. The framework also points to some management approaches, where suitable methodologies and tools for the improvement work may be found, and in what areas these tools can be applied. Furthermore, this management framework was used as a filter in order to describe the findings of the case study, see Chapter 6 (Case Description).
CONCLUSIONS AND DISCUSSION

The selected case was available through the participation in a research project, which was performed in cooperation with an industrial organisation. The main unit of analysis was the organisational improvement process, while subunits of analysis were methodologies and tools that supported this work. A number of processes, interrelationships between these processes, and supporting methodologies and tools were identified. The analysis of findings within the case study and the literature study answers the stated research questions, see Chapter 7 (Analysis and Results).

The initial literature study resulted in a theoretical management framework that in a holistic view describes how an organisation can work with continuous improvements. The framework also points to management approaches, where methodologies and tools that can support the organisational work with continuous improvements may be found.

The literature study and the case study were made in an iterative manner, where the two research strategies supported each other and findings in each strategy corroborated the other. The findings in the literature study and the case study were then merged into a conceptual model that describes how an organisation can combine a number of methodologies in order to systematise the work with continuous improvements. The methodologies that were included in the model also indicate what kind of tools can support the organisational work with continuous improvements. See Chapter 7 (Analysis and Results).

Both the framework and the model indicate what kinds of methodologies and tools can support the work with stakeholder focused continuous improvements of complex technical system functions. Thereby, the first research question is considered to have been answered.

The framework and the model also indicate how an organisation can work with continuous improvements of complex technical system functions in the context of dynamic stakeholder requirements. In this way the second research question is also considered to have been answered.

It is important to notice that the difference between the two research questions is in the level of unit of analysis. It may at a first glance seem that if one is answered so is also the other, but there is a difference. The first research question is on a more detailed level of methodologies and tools, while the second research question is on a more aggregated level, concerning a continuous improvement process. The combination of the two
research questions is seen as important in order to get a view that combines the two levels.

8.2 Discussion
There are a number of approaches that can be applied in the work with continuous improvements. In this study the three management approaches Quality Management, Requirements Management, and Health Management have been in focus. Each of these approaches has a specific focus and they complement each other.

The literature study indicates that Requirements Management mainly focuses on the management of stakeholder requirements, while Health Management focuses on the functions of technical systems. Hence the approaches of Requirements Management and Health Management complement each other. Quality Management is in this study used as a value-laden basis, upon which assumptions, interpretations, and conclusions are made. Hence, Quality Management gives a holistic view of the studied area and puts the pieces together to form a whole. This may be seen in the management framework, but also in the structuring of Health Management, which was presented in Chapter 3 (Perspectives on Presented Theories).

The management framework was also applied in order to decide upon what empirical data to collect, and how these empirical findings should be structured. The framework indicates, on a conceptual level, how an organisation can work with continuous improvements of complex technical systems.

The theoretical framework presented in this thesis is intended to support a systemic and systematic work with continuous improvements of complex technical systems, in the context of dynamic stakeholder requirements. The presentation of the framework is on a rather aggregated level, but may hopefully be beneficial for a diverse set of organisations, both those that develop technical systems and those that supply services. However, it is important to notice that an application of the framework on a more detailed level is probably strongly influenced by the environment of the specific organisation. As one example, an organisation that develops critical and very complex systems, as in the aerospace industry, will not manage requirements in the same way as an organisation that manufactures consumer products (see Sommerville & Sawyer, 1997; Kotonya & Sommerville, 1998).
One reason for the fruitful synergism between the three management areas is probably the systematisation, which is strengthened by the emphasis on the two measurements of stakeholder requirements and system functions, in order to enable fact-based decisions. Fact Based Decisions is a core value that together with Stakeholder Focus, Continuous Improvements, and System View are central in the presented framework. Core values that are not directly in focus in this thesis are, for instance, Management Commitment and Everybody’s Participation. The reason for this is not that they are considered unimportant. On the contrary, they are seen as crucial for the actual work with continuous improvements. These complementary core values are seen as important when selecting appropriate methodologies and tools, which may be found in the presented framework. The reason for this is probably that each management area has its own set of methodologies and tools, even though some can be shared by two or even all the three areas.

The practical result of the study may be summarised in the points below:

- A model that describes the systematic work with identification of what system functions to cover with tools from Health Management, based on the deployment of stakeholder requirements.
- Adaptation and combination of a number of methodologies and tools that support this work.

The methodologies and tools are adapted and combined in order to clarify the connection between stakeholder requirements and system functions. The framework and model, as presented here, focuses on identifying what functions to cover with tools from Health Management, based on stakeholder requirements. This focus gives a correspondence between stakeholder requirements and system functions. This enables traceability and it should therefore also be possible to verify and validate some of the stated stakeholder requirements. The requirements of the stakeholders indicate what functions to monitor and why these functions should be monitored. How the functions should be covered, and where in the system to implement the monitoring and test system, is not included in the presented framework and model.

Appropriate methodologies and tools for continuous improvements of complex technical systems may be found in the management framework presented in this thesis. One methodology that is common in Quality Management and that has been applied in Requirements Management is
Quality Function Deployment (QFD), see Macaulay (1996). It is believed that the thoughts in QFD may be valuable in a context of dynamic stakeholder requirements, see Herzwurm & Schockert (2003). One common tool that supports QFD is the House of Quality (HoQ), and this matrix diagram is believed to be beneficial in the described context, e.g. through the support of requirements traceability.

Another possible solution is probably to use self-assessment as a methodology and to support this work with some appropriate criteria booklet (such as the one used in the Malcolm Baldrige National Quality Award), see, for example, Campbell & Jardine (2001). A third possibility is to select and combine appropriate parts of the mentioned methodologies and tools. All the methodologies mentioned, QFD, self-assessment, FMEA, RCM, and SRA require stakeholder participation to a varying extent, and therefore they support core values that are not directly emphasised in this thesis, such as Management Commitment and Everybody's Participation.

8.3 Reliability and Validity

There are some aspects that should be considered when looking upon the result of the present study.

8.3.1 Literature Study

A wide range of different databases was covered in order to receive a number of different views on the studied management areas. This methodological choice may have resulted in key-references within the areas having been missed out, due to the huge amount of received information. If key-references have been missed out this would negatively affect the validity of the literature study. In the case of Quality Management this risk is considered to be rather small, since the author has done the research in an environment that is strongly permeated by the discipline.

Only English and Swedish publications were analysed, which may have resulted in the omission of relevant literature published in other languages. This second point might also contribute negatively to the validity of the literature study.

The taxonomy within and between different management areas are not consistent, which may have resulted in misinterpretation during the study. Once again the validity of the findings of the literature study is affected negatively. At the same time the documentation of the theories found within the literature is adapted to the author's view, which may influence the reliability negatively. However, by referring to the sources and
CONCLUSIONS AND DISCUSSION

appending a reference list the reliability should be affected positively. The author has also tried to write the thesis in a clear and simple manner, which will hopefully result in transparency and inter-subjectivity, and hence contribute to the reliability positively.

The author’s background in Quality Management probably influences the selections made during the study. It is difficult to cancel out the influence from the author. By adapting a formalised research design and applying the same units of analysis in the literature study as in the case study the subjective influence from the author is hopefully reduced. At the same time findings in the literature study and the case study have been discussed with both colleagues at the university and members of the project group in the studied case. These continuous discussions have probably contributed a multifaceted perspective on the phenomenon. The multifaceted perspective may be seen as a sort of triangulation, which should contribute positively to the validity of the literature study.

8.3.2 Case Study

Construct Validity
In the performed case study two types of units to study have been selected. The main unit of analysis is the organisational work with continuous improvements, as reflected by the second research question. The subunits of analysis are methodologies and tools that support the work with continuous improvements, as reflected by the first research question. One way of demonstrating that the selected measures of units reflect the units of analysis is by a correspondence between the theoretical descriptions of the units and the empirical findings. Since the documentation in both the case study and the literature study is rather extensive, at the same time as indicating the same findings, the construct validity should be strengthened.

In the case study document studies and interviews have been selected as two major sources of evidence, and some observations has also been made, in order to affect the internal validity positively. This application of multiple sources is a data triangulation. Since the collected case data is looked upon through theories from three management perspectives (the theoretical framework and the Programme-Logic Model) the construct validity should be affected positively, through a theoretical triangulation.

The author has tried to visualise a chain of evidence during the data collection. This has partly been possible through the formalised document procedures that exist at the case study, where references to related
documents may be found, and partly through persons that are responsible for the documents. However, since the collected documents are classified as confidential it is almost impossible for persons outside the company to get access to the documents referred to. This affects the construct validity negatively. In order to reduce the negative impact of classified documents the author has tried to eliminate the need for the documents in the case description and find unclassified literature with similar content instead. An attempt at enhancing the chain of evidence has also been made by means of a clear description of the study, from stated research questions to case study conclusions, which should also strengthen the study’s reliability.

Drafts of the thesis have also been studied by key informants, which should contribute positively to the construct validity.

External Validity
The external validity of the framework and the model has not been tested on a completely different case. However, the findings are tested in a limited application within the studied case. Since the conclusions of the case study are combined with some theories the external validity of these findings may hopefully be corroborated by the application. However, a major drawback is that the application is not finished when this thesis is written. It should be noted that the methodologies and tools that are included in the result of this thesis is well-known in many other cases, and thereby is the external validity strengthened.

Reliability
In order to affect the reliability positively both a case study protocol and a case study database have been constructed. However, due to the fact that a large amount of the collected data are classified as confidential, in regard to organisational interest or defence aspects, the reliability of the study is affected negatively. In order to affect the reliability positively, an attempt has been made at writing the thesis in such a way that transparency and inter-subjectivity are achieved. At the same time the parallel literature study may hopefully contribute positively to the reliability since the study has been performed iteratively between empirical and theoretical findings.
8.4 Further Research

Depending on the interest of the reader of this thesis there may be a great number of different aspects to consider for further research. The author of this thesis leaves some suggestions for further research that have emerged during the work, but were not pursued within the framework of the present study.

One extension of the present study would be to expand the purpose to an explanatory one. Hence, the Programme-Logic Model presented in Chapter 4 (Research Design) may be applied in order to explain continuous improvements of complex technical systems.

A focus on the core values Management Commitment and Everybody’s Participation, which are not in focus in this thesis; is a possible further study. Another way of broadening the study is to a focus on more sociological issues in the presented framework. This is one important aspect that is crucial in the actual work with continuous improvements of complex technical systems. At the same time the author has observed that there does not seem to be any difficulty for people involved in the operation and support in the aerospace community to report incidents, accidents, and failures. The reason for this is probably that the consciousness of the importance of safety seems to be very high. When a person reports an incident or a failure the efforts are focused on eliminating the problem, and not on finding someone to blame. In this way an open climate that can act as a benchmark for other areas exists in the aerospace community. The safety consciousness also seems to strengthen the view of maintenance as something important and contributory, instead of something that is a necessary evil, which often exists in other areas. A study of the safety culture in the aerospace community, what it depends on, and how it can be transferred to other areas, are examples of interesting research that is related to the work presented in this thesis.

Another possibility for further research is to develop the improvement framework and model by a stronger focus on the earlier phases, which includes identification of stakeholders and their requirements, and the prioritising of requirements with respect to monitoring and testing, on the basis of system safety, reliability, and product support perspective. This work is crucial in order for an organisation to be able to fulfil, and hopefully exceed, the requirements of the stakeholders. This includes difficulties such as deciding upon where to draw the boundaries of the stakeholder system, that is, to decide who should be included, and who
should be omitted, and why. Another difficulty is to know how to prioritise
the requirements of the included stakeholders. An organisation has limited
resources and it is therefore necessary to prioritise the requirements in
some appropriate way.

Some of the most important stakeholders of an organisation are the
customers, who are the stakeholders that pay for the product. Hence it is of
major interest to develop an approach to formulating contractual
requirements, which, after deployment, can be applied in order to design
and verify the function of the system for monitoring and testing. Here
aspects of formulating good requirements and understanding the
customers are of the greatest importance, but also being aware of the
developing organisation’s capabilities. It is also interesting to identify or
develop decision criteria that can be applied in order to decide what system
functions should be monitored and tested. Aspects of how health data and
information can support the verification and validation of system functions
pragmatically are also of interest, in order to close the loop between
stakeholder requirements and system functions.

Another possibility is to study how the proposed framework can be
implemented in an organisation. Here aspects such as the integration of
proposed methodologies and tools with other methodologies and tools that
have shared interfaces or functions are crucial. As one example, it seems as
if the border between the technical system and the support system is
becoming fuzzier due to an integration of traditional support
documentation, such as fault localisation and other instructions, in the
built-in system for Health Management. Another important aspect here is
that of computerisation and software support of the work with stakeholder
requirements and system functions, which seems natural since health data
and information are intended to be collected once the technical system is in
the operational phase. An implementation of something new also means
that there are some organisational changes that must be considered. Once
again core values such as Management Commitment and Everybody’s
Participation are probably of great importance. In order to evaluate the
practical contribution and value of the proposed framework and model a
pilot study may be valuable. This pilot study would also contribute
positively to the present study’s external validity. See Söderholm (2003b).
REFERENCES


REFERENCES


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REFERENCES


REFERENCES


REFERENCES


REFERENCES


REFERENCES


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REFERENCES


APPENDED PAPERS

PAPER A


PAPER B


PAPER C

AEROSPACE DIAGNOSTICS AND PROGNOSTICS IN A TQM-PERSPECTIVE

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ABSTRACT

In this paper a management system view of TQM, consisting of values, methodologies, and tools, is briefly presented. This holistic view is then used as a filter to map and structure some of the current research and practice within the field of aerospace diagnostics and prognostics. Also a number of core values and their interrelationship with some methodologies and tools for diagnostics and prognostics are briefly discussed. Finally a short presentation of the management of product support requirements, and a research project related to this area, performed by the Centre for Dependability and Maintenance in cooperation with Saab Aerospace, is presented.

KEYWORDS

Aerospace, Diagnostics, Prognostics, Total Quality Management, Values, Methodologies, Tools, Requirements Management, Product Support, Supportability

INTRODUCTION

The aerospace industry has during the past ten years been characterized by worldwide changes. These changes are partly caused by the rationalization and concentration process of the aerospace industry and partly by lack of willing military customers due to severe cuts in defence budgets. This, in connection with fierce competition, forces the airplane industry to design for customer requirements as key-buying factors. [1]

One consequence of the reduced defence budgets is that the customers requirements on availability performance and life support cost over the product life cycle has increased and the reduction of maintenance and support cost has become more essential [2]. These requirements can be divided into two different needs. Firstly to sustain commercial operations without interruption, and secondly to minimise operating, maintenance and support costs. “Sustaining operations,” means maximising the
availability of the aircraft within a fleet and then ensuring that each time the aircraft is being used it remains "operational reliable" and completes its flight without interruption. "Minimising operating, maintenance and support costs," means reducing the amount of maintenance labour required and reducing the logistic support required [3]. To meet these requirements condition monitoring (CM) and condition based maintenance (CBM) can be employed. These approaches can significantly reduce life cycle costs by eliminating unnecessary inspections, minimizing inspection time and effort, and extending the useful life of new and aging aerospace structural components [4].

Two important activities related to CM, that facilitates CBM, and other product support approaches, are diagnostics and its extension towards prognostics. This extension is possible thanks to new technological advances in sensors and failure analysis and is a revolution in the way large systems, such as aircrafts, can be maintained. It is a breakthrough that promises not only more efficient operations and reduced maintenance cost, but also the saving of lives. [5]

To map and structure the field of aerospace diagnostics and prognostics, keeping the customer focus in mind, the view of a management system can be valuable (see for example Total Quality Management [6] and Dependability Management [7]). This system view can also be helpful for the selection of appropriate methodologies and tools to support some of the core values that are of principal importance for the long-term competitiveness of a company.

**STUDY APPROACH**

This paper is a short presentation of the initial steps in one of the earliest phases of a research project related to the management of requirements in aerospace diagnostics and prognostics. The purpose of this phase was to map and structure the field of aerospace diagnostics and prognostics. It is essentially a theoretical discussion based on a literature study.

The literature study is based on a literature search with a following literature review. Initially a number of search words (see table 1) were used in different combinations. The literature search has been conducted in a number of databases and search engines (see table 2). When appropriate literature was found additional search words (such as health management and product support) and references were found. However, these are not presented in this paper.

The literature search resulted in a number of books, conference proceedings, theses, technical reports, electronic sources, and articles from journals, magazines and newspapers.

The abstract of practical retrievable literature, with interesting titles, were read through. Literatures with interesting abstracts were read in whole. The result of this literature review has been coarsely mapped and structured by the use of a filter based on a management system view of Total Quality Management (TQM). This work will continue and be more finely in the future.

**TABLE 1. SEARCH WORDS THAT HAVE BEEN APPLIED IN THE INITIAL LITERATURE SEARCH. THE "*" SYMBOLISES USED TRUNCATIONS.**

<table>
<thead>
<tr>
<th>Initial search words</th>
</tr>
</thead>
</table>
TABLE 2. THE SOURCES WHERE THE LITERATURES SEARCH HAVE BEEN CONDUCTED.

<table>
<thead>
<tr>
<th>Databases</th>
<th>Search engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>• American Institute of Aeronautics &amp; Astronautics (1996-)</td>
<td>• Alta Vista</td>
</tr>
<tr>
<td>• Applied Science and Technology Plus (1983-)</td>
<td>• Google</td>
</tr>
<tr>
<td>• Applied Science and Technology (1997-)</td>
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THE TOTAL QUALITY MANAGEMENT SYSTEM

Total Quality Management (TQM) can be seen as a management system in the sense of Deming, as "a network of interdependent components that work together to try to accomplish the aim of the system" (see [8], p.50). This statement is also valid for, as some examples, Dependability Management and Total Productive Maintenance (TPM), and to some extent also for Reliability Centred Maintenance (RCM). The management system consists of the three interdependent components: values, methodologies, and tools. These three components are interdependent of each other and support each other. The core values are also in the literature named principles, dimensions, elements or corner stones. The term core value is to prefer, since it is a way to emphasise that these statements should work together to constitute the culture of the organisation, and that they accordingly are basic concepts. The core values constitute a very important component as they are the basis for the culture of the organisation and also the basis for the goals set by the organisation.

The number of values, and the naming of them, differs between different descriptions of TQM and its elements (see table 3). There is however some common core of meaning in the values that can be found in some of the literature, and these core values can be seen as the foundation of TQM [9] (see figure 1). Another component is a set of methodologies, which is ways to work within the organisation to reach the goals. A methodology consists of a number of activities performed in a certain order and it can sometimes be useful to describe it as a process. A third component is a set of tools, which is rather concrete and well defined. Sometimes these tools have a statistical basis, to support decision-making or facilitate analysis of data.

The management system is not stationary but is continuously evolving. Some core values might change, and particularly the interpretation of some of them may develop. In addition new methodologies will appear or be transferred from other management theories. New tools will develop and others will be taken from other disciplines. It is important to point out that the management system should be looked upon as a system. It is often the case that a certain core value is necessary for the
A positive result of the usage of a system view, as described above, is that it focuses on the totality. Hopefully it will reduce the risk that an organisation picks up just a few parts of the system. It is essential to start with the core values and decide upon which core values should characterise the organisation. When that is decided it is necessary to identify methodologies that are appropriate for use in the organisation and that support the chosen core values. Finally, following that decision the suitable tools have to be identified and used in an efficient way to support the methodologies. It is important to point out that a particular methodology can support different core values and the same tool can be useful within many methodologies. It is of course beneficial for the corporate culture to use methodologies and tools that support several values.
Aim: Increase external and internal customer satisfaction with a reduced amount of resources

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**Figure 1.** Total Quality Management (TQM) seen as a continuously evolving management system consisting of core values, methodologies and tools. It is important to note that the methodologies and tools in the figure are just examples and not a complete list. In the same way the core values may also vary a little between different organisations and over time. (After [6], p. 241).

**AEROSPACE DIAGNOSTICS AND PROGNOSTICS**

There are a number of changes that can be identified within the field of aerospace diagnostics and prognostics. Three of these changes are (i) the extension of diagnostics towards prognostics, (ii) the expanded system view, and (iii) the aggregation of autonomy upward in the system hierarchy. These changes are interdependent of each other and closely related. They are possible due to advances in sensor and analysis technology and answers to increased customers’ demands on enhanced supportability.

**Values**

The core value "customer focus" is of increasing importance for the aerospace industry, which in turn has resulted in the need for focus on some other core values. One such core value can be named “system view”. Various health-monitoring technologies aiding in the detection and classification of developing system faults have been developed. Traditionally these technologies have focused on fault detection and isolation within an individual subsystem. However, a change that can be seen is the integration of anomaly, diagnostic and prognostic technologies across subsystems and systems (see for example [4] and [13]). It should be noticed that the expanded system view does not stop at the system platform level. The on-board and ground based diagnostics and prognostics are integrated with each other as well as with decision support and logistic systems (see for example [14] and [15]).

The customer focus has also resulted in the extension of autonomy upward in the system hierarchy, which is an answer to the growing demand for autonomous operation [3]. This change is present both in the system platform and in its context (see for example [14]). This approach is strongly connected to the expanded system view.
Methodologies

Methodologies within the area of health management can often be traced by some acronym. Examples of this are CM (Condition Monitoring), FDIR (Fault Detection, Isolation and Reconfiguration), VHM (Vehicle Health Monitoring), CBM (Condition Based Maintenance), IM (Informed Maintenance), PHM (Prognostics and Health Management), and SHM (Structural Health Management or System Health Management) etcetera. Different acronyms can have the same meaning and the same acronym can have different meaning, depending on the source. One of the reasons for this is that the different methodologies have evolved over time, more or less dependent of each other. There also exist methodologies that do not have an acronym.

The management system view can in this situation be helpful to clarify what really is meant in different descriptions. Is it a methodology or a tool that are intended? Or is it even a management system that is described?

One change, within aerospace health management, is the extension of diagnostics towards prognostics. Fault diagnosis is actions taken for fault recognition, fault localization and cause identification [16]. Prognostics can from this be defined as actions taken so that potential faults and failures can be identified, localised, and predicted. The aim of prognostics is to stop critical failures before they occur. The concept of prognostics is an extension of diagnostics, in which the sensor data are simply monitored for the occurrence of anomalies or failures that are then corrected. The prognostics procedure is analogous to the way a doctor deal with medical problems. First the problem is detected, and then a diagnosis is made on the failure mode and its severity. It is also essential to predict the development of the failure in order to estimate the remaining useful life of the machine. See for example [5] and [13]. Diagnostics and prognostics can be seen as, according to the above discussion, methodologies. In the same way CM and CBM can be seen as methodologies, even if different descriptions can have different meaning. CM can be described as the monitoring of the condition (or “health”) of a system. This monitoring results in collected data that represent the condition in some way. However, the interpretation of the collected data and the following conclusion about the systems condition is diagnostics. It is probably valuable to make this distinction between CM and diagnostics.

PHM and SHM can be seen as management systems. Most descriptions of them contain different methodologies and tools. However the core values are missing. Some core values are frequently seen behind the description, but they are very seldom articulated. This also makes it possible to see PHM and SHM as methodologies that structures and combine other methodologies and tools in an effective and efficient way. A parallel can be drawn to the area of quality management. Here some abandon TQM for Six Sigma and think that they get something completely new. Six Sigma should be seen as a methodology, within TQM, that combine and structure existing, and established, methodologies and tools. Core values that are supported by Six Sigma are “process focus” and “base decisions on facts”. A methodology, within Six Sigma, is SPC (Statistical Process Control) and one of the most common tools that support SPC is probably the control chart. One thing that is new with Six Sigma is the structure and the packaging. However, if the core value “top management commitment” is not present the chosen approach will probably fail, whatever it is called.

Tools

Tools within the area of aerospace health management are often software that is built on algorithms and models. The algorithms can, for example, be reasoning algorithms [15]. The models can contain the information on how components, subsystem and systems interact in operation. In addition, the model can contain information of how the system failure modes, sensors, and health monitoring technologies are related. This is necessary in order for failure symptoms and failure propagation to be traced back to root cause failures for fault isolation purposes [13]. Another possibility is statistical
models based on historical data. These tools support both diagnostics and prognostics. An approach that enables this change is artificial intelligence (AI), which can be used for sensor [17], data and knowledge fusion (see for example [18], [19], [20]).

Another important approach is information technology. This makes it possible to tie together the systems internally and externally. Internal from sensors through processors and reasoning algorithms, etcetera and external between different system platforms and to ground based system. These tools are clearly related to diagnostics and prognostics.

Equipment is technological devices and hardware that supports chosen methodologies and tools. They are on a “lower” level then tools. In recent years there has been a vast development in this area that supports the evolution in aerospace health management. Examples of equipment in aerospace health management are sensors, MEMS (Micro Electrical Mechanical Systems), and processors (see for example [21]). It is probably to a large extent the development of equipment that has enabled the realisation of the three changes mentioned in this paper.

REQUIREMENTS MANAGEMENT

For a combat aircraft the operational phase is about 30 years. To be able to keep the operational and support cost of the future under control the focus should be on the decisions taken in the earliest phases of the products life cycle. These phases are conception, definition, and design. [2]

The most fundamental issue for the aircraft designer in the early definition phases of the design process is the effect that requirements have on the system. Requirements drive initial design studies, procurement decisions, and ultimately operational effectiveness and cost. [22]

Mission and program goals, such as, safety, mission reliability, and life cycle cost can be fulfilled with CM, and diagnostics and prognostics capabilities that enables the user to practice different product support activities, such as CBM.

However, the requirements span a much wider range of topics than aggregated goals and technical issues. These include user needs, investment and business requirements, operational issues, regulatory issues, as well as engineering and manufacturing requirements. (See [23] and [24])

The enlargement of autonomy in the system is present in both the system platform and in its context. However, the interface to the human is only moved upward in the information chain. In the end a human being will inevitably take part of the information and has to act on it. The aerospace industry should identify the users and their requirements on a system for diagnostics and prognostics at these interfaces. The understanding of the requirements for specific users, such as pilots, technicians, and planers etcetera on a system for diagnostics and prognostics can probably be improved. These users are facing completely new systems that are more complex then before. An increasing amount of information is gathered, and more sophisticated information analysis models are offered. Today’s system can easily overwhelm any user with condition information, and only the most experienced users and experts can sort, prioritise and interpret the information effectively [25]. At the same time very little interaction between program activities associated with operation and maintenance exists. In spite of the fact that the data and technologies used to support these activities and the individual efforts associated with these activities contains significant overlap [26].

The reason for this unsatisfactory situation is that the choice of appropriate methodologies and tools often is made according to personal experience and knowledge. However, this choice should be influenced by some management philosophy, based on a number of core values. The core values have
a great influence on the choice of strategies for accomplishing different kind of goals, for example regarding dependability, availability, safety and other aspects of customer satisfaction. The strategies will in turn include the use of appropriate methodologies and tools. There seems to be a growing practice towards this way of thinking in the aerospace industry, but any empirical finding for this statement has not been identified. There is also a question of how systematic this practice actually is.

The aerospace industry should design the systems for diagnostics and prognostics so that it fulfils the customers' requirements. In this situation the core values “customer focus” and “base decisions on facts” is essential. To enable this it is necessary to identify the specific requirements that the different customers to a system for diagnostics and prognostics has.

A user-guided, system-development approach, which consider a balance of operational, technological, legal and economic factors from the earliest phases of development should be taken to allow the most quick implementation, and useful practice of a health management system. [23]

FUTURE ACTIVITIES

The Centre for Dependability and Maintenance is performing a research project in cooperation with Saab Aerospace. The aim of the research is to identify and apply methodologies and tools for a systematic management of requirements. The primary focus will be on external requirements and not the internal ones. The approach will be based on the presented management system view.

The result of the research will be a generic process for a systematic management of requirements in the design of the system platform and their product support systems. The process will be based on the core values of TQM and the Shewhart-cycle (see [27]). In each step in the cycle a pool of methodologies and tools, which support the core values and each other will be identified.

By defining a requirements management process that constitutes of a number of activities that include methodologies and tools it will hopefully be possible to identify, prioritise, and transfer the customers’, and other, requirement, to a solution that meets, and hopefully exceeds, the stated requirements.

A common methodology in the translation of customer requirements into appropriate company requirements at each stage from research and product development engineering and manufacturing to marketing and distribution is Quality Function Deployment (QFD). The Quality House is a tool that can be used within that methodology. (See for example [28])

In aerospace diagnostics and prognostics a requirements management process will hopefully make it possible to choose and combine appropriate methodologies and tools from the big smorgasbord that are available. It will also make it possible to see what customisations and/or developments of existing methodologies and tools that might be necessary to make. To support this work the structuring and mapping of product support management will continue and be both more concrete and more explicit.

CONCLUSIONS

The authors believe that the management system view can facilitate for organisations to work with different management matters since things are put together to create a whole. The area of application is probably only limited by the human imagination. The important thing is not what the system is called, but how it is composed. In this paper the system view has been used for an initial mapping and structuring of the field of aerospace diagnostics and prognostics. This work will be further developed and enhanced. The system view will also be used in the creation of a requirement management
process. Hopefully, this approach will decrease the risk as seeing the world as consisting of nails only, just because you have been given a hammer and a short instruction on its most elementary use.

ACKNOWLEDGEMENT

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CONTINUOUS IMPROVEMENTS OF COMPLEX TECHNICAL SYSTEMS:
A THEORETICAL QUALITY MANAGEMENT FRAMEWORK SUPPORTED BY REQUIREMENTS MANAGEMENT AND HEALTH MANAGEMENT

CONTINUOUS IMPROVEMENTS OF COMPLEX TECHNICAL SYSTEMS

A THEORETICAL QUALITY MANAGEMENT FRAMEWORK SUPPORTED BY REQUIREMENTS MANAGEMENT AND HEALTH MANAGEMENT

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ABSTRACT
Continuous Improvements are a core value of Quality Management. This work is often a response to changed stakeholder requirements. However, the increasing complexity and criticality of many of today's technical systems require that the improvement work is systematic, in order to properly manage the changes and avoid unwanted effects. This paper explores how Requirements Management and Health Management can support Quality Management, in order to systematise the management of continuous improvements of complex technical systems in response to changed stakeholder requirements. The result is a theoretical management framework based on a combination of the three management areas. The framework is intended to facilitate a systematic work with continuous improvements of complex technical systems, in the context of dynamic stakeholder requirements.

KEYWORDS
Quality Management, Requirements Management, Health Management, Stakeholder Focus, Continuous Improvements, Fact Based Decisions, Complex Technical System

INTRODUCTION
Continuous Improvements, which are a core value of Quality Management, are often actions related to changed stakeholder needs and requirements. It is also frequently stressed that the decisions for improvements should be based on relevant facts that are founded on performed measurements. The reason for the work with continuous improvements is to increase stakeholder satisfaction, with a decreased amount of resources. (See, for example, Shewhart, 1980; Juran, 1992; Deming, 1993)

Complex technical systems often have a rather long life time (see, for example, White & Edwards, 1995; Sandberg & Strömberg, 1999), e.g. 30 years for a combat
aircraft. The requirements on these systems change over time due to the technical
development, and changes in the needs of stakeholders, operational environment,
laws and regulation (see North et al., 1998; Juran, 1992; Kotonya & Sommerville,
1998; Herzwurm & Schockert, 2003). The changing requirements drive system
evolution and continuous improvements, in order to maintain a high level of
stakeholder satisfaction also after delivery of the system (see North et al., 1998;

Many complex technical systems of today are also critical ones with stringent
requirements on reliability, availability, maintainability, security, and safety (e.g.
aircraft, nuclear power plants, and spacecraft). For some complex technical
systems the requirements on lower cost of operation and support throughout the
system’s life cycle have also grown in importance (see, for example, Moubray,
1997; Cini & Griffith, 1999; Sandberg & Strömberg, 1999; Schmidt, 2001). When the
technical system is both complex and critical it is even more important that the
work with stakeholder focused continuous improvements is performed in a
systematic way, in order to avoid unwanted effects, such as human death or
injury, damage to or loss of technical system or property, or environmental
damage.

An approach to managing dynamic stakeholder requirements throughout the
technical system’s whole life cycle is Requirements Management, which
encompasses methodologies and tools for the management of changing
stakeholder requirements (see, for example, Davis & Leffingwell, 1996; Macaulay,
and safety of a critical system, and also to minimising the combined cost of
operation and support throughout the life of the technical system, is Health
Management, which includes methodologies and tools for the management of the
health, or condition, of a system (see, for example, Mobley, 1990; Becker et al.,
1998; Litt et al., 2000; Baroth et al., 2001; Campbell & Jardine, 2001; Dunne et al.,
2001; Hess & Fila, 2002).

The purpose of this paper is to explore how Requirements Management and
Health Management can support Quality Management, in order to systematise
the management of continuous improvements of complex technical systems in the
context of dynamic stakeholder requirements.

Below a short description is given of the approach that was applied in order to
fulfil the purpose. After that a review of Quality Management and aspects of
quality in complex and dynamic systems are presented. Then, reviews of
Requirements Management and Health Management are given. Thereafter, the
three management areas are combined in a management framework. Finally,
some aspects of the presented framework are discussed and suggestions for
further research are indicated.
STUDY APPROACH

In accordance with the criteria given by Yin (1994) a literature study was selected as an appropriate research strategy in order to answer the stated research question. The literature study covered mainly Requirements Management and Health Management, but some complementary references for Quality Management were also taken into account. The activities performed and the outcomes achieved within the literature study are summarised in Figure 1.

Figure 1. The activities performed and outcomes achieved during the literature study.

The analysis of interesting literature was mainly based on a theoretical filter of a system view on Quality Management (see Hellsten & Klefsjö, 2000). The analysis resulted in affinity diagrams that described Requirements Management and Health Management as two management systems. Finally, the three management areas were united in a management framework. During the study continuous meetings and discussions with industry and colleagues were performed.

QUALITY MANAGEMENT

Garvin (1988) uses five different approaches to define quality, and concludes that it may be beneficial to be aware of multiple approaches and actively shift one’s approach when the product moves from design to market. Some key-phrases about quality in literature are “Quality means conformance to requirements” (Philip B. Crosby), “Quality is fitness for use” (Joseph M. Juran), “Quality should be aimed at the needs of the customer, present and future” (W. Edwards Deming), “the lack of quality is the losses a product imparts to the society from the time the product is shipped” (Genichi Taguchi). In the above definitions of quality the focus on customers and their needs is obvious. Deming has expanded the customer focus to include future customers, and Taguchi stresses that the losses for the whole society after delivery of the product should be considered, a view which is related to today’s concept of sustainable development.
The evolution of Quality Management may be described in different ways. One common description is made up of four stages that follow each other. These stages are Quality Inspection, Quality Control, Quality Assurance, and Quality Management (see, for example, Garvin, 1988; Dale, 1999). Kroslid (1998) describes another evolution of Quality Management. In this description there are two different schools of Quality Management. One is the “deterministic school of thoughts” and the other is the “continuous improvement school of thoughts”. These two schools form a dual path of the evolution of Quality Management, in contrast to the single evolutionary path described by Garvin (1988) and Dale (1999).

The deterministic school of thoughts may be seen as related to Quality Inspection and Quality Assurance. This part of Quality Management starts with Frederick W. Taylor in the end of the 19th century. Taylor’s ideas were followed by British and American military standards, which later became the basis of ISO9000. The continuous improvement school of thoughts, which focuses on variation and improvements, may be seen as related to Quality Control and Quality Management. This part of Quality Management may be traced back to Walter A. Shewhart in the 1930s.

The view and naming of Quality Management also differ between different descriptions. Some authors have suggested a system approach to the concept (see e.g. Shiba et al., 1993; Dean & Bowen, 1994; Hellsten & Klefsjö, 2000). According to Hellsten & Klefsjö (2000) Quality Management may be seen as a management system that aims at increased external and internal customer satisfaction with a reduced amount of resources. This management system consists of the three interdependent elements values, methodologies, and tools (see Figure 2).

That the core values are fundamental to Quality Management is commonly stressed (see e.g. Oakland, 1993; Kanji & Asher, 1993; Lewis, 1996; Boaden, 1997). According to Hellsten & Klefsjö (2000) the core values constitute a very important element as they are the basis for the culture of the organisation and also the basis for goals set by the organisation. However, the naming, formulation, and number of core values differ. In the Malcolm Baldrige National Quality Award 11 “core values and concepts” may be found while Dale (1999) discusses eight “key elements”, and ISO9000 includes eight “management principles”. Sila & Ebrahimpour (2002) found, in a thorough literature review, seven “factors” that were most frequently covered within published Quality Management survey based research during 11 years. In all the sources described above core values such as Customer Focus, Continuous Improvements, and Fact Based Decisions are central.
Another element of the management system is a set of methodologies, which are ways to work within the organisation to reach the goals. The third element within the management system consists of tools, which are fairly concrete and well defined. Sometimes these tools have a statistical basis to support decision-making or facilitate the analysis of data. (See Hellsten & Klefsjö, 2000)

**QUALITY IN DYNAMIC AND COMPLEX SYSTEMS**

There are a lot of different views and definitions of what a system is. According to ISO/IEC 15288 (2002) a system may be viewed as “a combination of interacting elements organised to achieve one or more stated purposes”. Deming (1993) states, “a system is a network of interdependent components that work together to try to accomplish the aim of the system”. Another definition is that “a system is a deterministic entity comprising an interacting collection of discrete elements” (NUREG-0492, 1981).

The definitions above all have roughly the same meaning. There are a number of elements that interact to achieve an aim. The interaction between the elements ensures that the system is something more than the sum of the individual elements, and the interaction between the elements also means that if any element
changes in some way, e.g. due to failure or modification, the system will also change (NUREG-0492, 1981). In this view the complexity of a system may be measured in terms of the numbers of elements, and the number and attributes of the relationships between elements (Flood & Carson, 1993). This means that the complexity of a system increases with the number of elements, the number of relationships between the elements, and the attributes of the relationships.

**Stakeholder System**
That the customer focus should include internal as well as external customers is commonly stressed in the quality literature (see, for example, Deming, 1993; Oakland, 1993; Juran & Godfrey, 1999). According to North et al. (1998) the external customers also include the community, the general public, and the shareholders. This expanded view of customers is in line with the one given by Juran & Godfrey (1999, p. 2.3), where customers are seen as “anyone who is affected by the product or by the process used to produce the product”.

The expanded view of customers, outlined above, may implicate that it is more appropriate to talk about “stakeholders” instead of “customers”. A stakeholder may be defined as (ISO/IEC 15288, 2002): “an interested part having a right, share or claim in the system or in its possession of characteristics that meet that party’s needs and/or expectations”. In this definition stakeholders include, but are not limited to, users, supporters, developers, producers, trainers, maintainers, disposers, acquirer and supplier organisations, regulatory bodies and members of the society. Therefore, “customer” is seen as one category within the larger domain of “stakeholder” in the remaining part of this paper. The core value Customer Focus is therefore replaced with Stakeholder Focus.

Checkland (1999) describes human activity systems. Such a system is a notational purposive system, which expresses some purposeful human activity. The system is notational since it is not a description of real-world activities, but an intellectual construct. In this paper the stakeholders of a technical system are viewed as elements in a stakeholder system. The interrelationship between the stakeholders and between the stakeholders and the technical system is expressed by requirements, which are further discussed in the section named “Requirements Management”.

One example of a simple stakeholder system is described by Juran (1992). This system consists of the three interdependent elements supplier, processor, and customer. The supplier provides something to its customer. The supplier’s customer, i.e. the processor, processes this input to some output, which in turn is delivered to the processor’s customer. Therefore each processor is also a customer and a supplier. In addition to this, each processor may have multiple suppliers and customers. It is fairly obvious that even this simple stakeholder system in reality may become rather complex.
In order to implement the core value Stakeholder Focus within an organisation and be able to harvest its potential benefits, it is necessary to select appropriate methodologies and tools that may handle the complexity and dynamic nature of the stakeholder system. We believe that these supporting methodologies and tools may be found in the area of Requirements Management, which will be discussed in some more detail later in this paper.

Technical System
A technical system may be defined as "a general category of artificial deterministic systems that performs the necessary effects to achieve the transformation of operands". Technical system is a collective term for machine systems, devices, apparatus, equipment, and plants. (Hubka, 1982)

Complex technical systems often have a rather long life time (see, for example, White & Edwards, 1995; Sandberg & Strömberg, 1999). As one example a combat aircraft typically has a lifetime of about 30 years (see Sandberg & Strömberg, 1999). The requirements on these systems change over time due to the technological development, and changes in the needs of stakeholders, operational environment, laws and regulation (see North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm & Schockert, 2003). In order to maintain a high level of stakeholder satisfaction throughout the whole life cycle of the system it has to be continuously improved (see Kotonya & Somerville, 1998; Herzwurm & Schockert, 2003).

Many complex technical systems of today are also critical ones, with stringent requirements on reliability, availability, maintainability, security, and safety (Sommerville & Sawyer, 1997), e.g. aircrafts, nuclear power plants, and spacecrafts. Safety critical is a term that may be applied to a condition, event, operation, process or item whose proper recognition, control, performance or tolerance is essential to safe system operation or use, for example safety critical system, element, or function (MIL-STD-882C, 1993). Safety may be seen as freedom from conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment (MIL-STD-882D, 2000). For some complex technical systems the requirements on lower cost of operation and support throughout the system's life cycle also have grown in importance (see, for example, Moubray, 1997; Cini & Griffith, 1999; Sandberg & Strömberg, 1999; Schmidt, 2001).

In order to meet the increasing demands for lower operation and support cost many complex technical systems are designed for Health Management. This design also gives a potential to improve issues such as reliability and safety, which are important when the system is a critical one. However, we believe that methodologies and tools within Health Management, which will be discussed later in this paper, may also support a realization of the core value Continuous Improvements, in particular when the technical system is complex and critical.
REQUIREMENTS MANAGEMENT

There are different definitions of requirements. According to ISO/IEC 15288 (2002) "stakeholder requirements are expressed in terms of the needs, wants, desires, expectations and perceived constraints of identified stakeholders." Stakeholder requirements include, but are not limited to, the needs and requirements imposed by society, the constraints imposed by an acquiring organisation and the capabilities and limiting characteristics of operator staff. Davis (1993) defines a requirement as "a user need or necessary feature, function, or attribute of a system that may be sensed from a position external to that system".

The definition that is applied in this paper is the one given by ISO/IEC 15288 (2002), but the stakeholders should also include those that not are identified, even though these stakeholders, of course, may be difficult to handle in practical work. If "user" is replaced by "stakeholder" in the definition given by Davis (1993), this one may also serve as an appropriate definition for this paper.

Requirements Management may be seen as an approach that has been developed within the computer industry and science, in response to increasing demands and costly failures (see, for example, Davis, 1993; Alexander, 1997). The trends that have had a powerful impact on the development of Requirements Management may be summarised as follows (see Alexander, 1997):

- Falling prices and increasing accessibility of computer-based systems.
- Growing interactivity, bringing a widening range of users with rising expectations.
- Increasing memory and program size, causing problems of complexity.
- Rising size and cost of system failures despite ever-better development tools.

According to Davis & Leffingwell (1996), Requirements Management is a systematic approach to eliciting, organising, documenting, and managing both the initial and the changing requirements of a system. A principal result of this work is the development of one or more requirements specifications, which define and document the complete external behaviour of the system to be constructed. Davis & Leffingwell (1996) regard Requirements Management as partly a management process and partly an engineering discipline, and state that it therefore may be used effectively to manage both technical complexity and requirements on the system.

Kotonya & Sommerville (1998) describe Requirements Management as the managing of changes in the requirements, and the relationship between requirements on a system. Requirements Management checks that it is technically and economically possible to perform proposed changes. If the change applies to a specific requirement it is important to check which other requirements may be affected. This requires that links between requirements, the sources of
requirements and the system design must be recorded, i.e. traceability information.

Requirements Management includes methodologies and tools to establish and execute a formal procedure to collect, verify, consider, and study how changes affect the system (Kotonya & Sommerville, 1998). Thereby, Requirements Management may be seen as a way to manage mainly four activities by the feedback from these activities (Bohner & Arnold, 1996), see Figure 3. The first step is to study the proposed change and make decisions about necessary changes and appropriate actions, based on wanted and unwanted effects of the change. After that, the changes must be specified and designed. The changes must then be executed based on the specification, e.g. through document changes. Finally, the performed changes must be studied to see if they meet the new requirements, and that the system meets existing requirements.

![Figure 3. Requirements Management supported by four interrelated activities. Inspired by Bohner & Arnold (1996).](image)

One major difference between the views on Requirements Management that may be seen in the descriptions by Davis & Leffingwell (1996) and Kotonya & Sommerville (1998) is that the former includes both initial and changing requirements, while the latter focuses on changing requirements. The work with initial requirements is called Requirements Engineering by Kotonya & Sommerville (1998). In this paper Requirements Management is seen as related to both initial and changing requirements, since the methodologies and tools for the work with requirements are very closely connected to each other, and also due to the iterative nature of the work with requirements. At the same time an initial requirement may be seen as a change from the state of no requirement at all. However, it should be noted that the distinction between Requirements Engineering and Requirements Management is quite common in the literature, at the same time as both the meaning and the naming may differ between different descriptions.

**HEALTH MANAGEMENT**

The health, or condition, of a technical system changes over time, since the elements within the system are subjected to degradation, which sooner or later will lead to failure of the system. These effects may be due to ageing, design configuration, environment, and abuse of the system. According to Nowlan & Heap (1978, p.18) “a failure is an unsatisfactory condition”. This unsatisfactory
condition is related to the design requirements, but also to user requirements, and the consequences of failure in the particular operating context.

The evolution of Health Management may be viewed in the light of some trends seen in the description of technical systems and their maintenance made by Moubray (1997):

- Growing dependence on technical systems that become more complex, which made availability and reliability aspects more important.
- Growing awareness on safety and environmental issues due to the negative impact that an increased amount of failures of technical systems had on these issues.
- Increasing focus on operation and support costs of technical systems since these costs increased over time.
- Changes within maintenance from corrective actions, via preventive actions towards predictive actions.

One approach, intended to meet the increasing demands on technical systems was Reliability-Centered Maintenance, RCM (see Nowlan & Heap, 1978). One vital contribution of RCM is the definition of potential failure, which led to the concept of Condition Based Maintenance (CBM) being accepted as one of the best ways of preventing functional failure (Coetzee, 1997). This in turn, led to a completely new business, providing tools for the monitoring of system health, being developed (Coetzee, 1997).

To enable CBM, the health of the system must be monitored, i.e. by condition monitoring (CM), which results in collected data that represent the system health in some way (Mobley, 1990; Martin, 1993; Campbell & Jardine, 2001). Diagnostics is concerned with the interpretation of collected health data and the conclusion drawn about the system’s current health (Martin, 1993). Based on the diagnostic information decisions about condition based maintenance may be made (Mobley, 1990; Campbell & Jardine, 2001 Litt et al., 2000; Hess & Fila, 2002). An extension of diagnostics is prognostics, which tries to predict the future health of a technical system (Becker et al., 1998; Söderholm & Akersten, 2002).

The aim of prognostics is to prevent critical functional failures before they occur (see, for example, Mobley, 1990; Becker et al., 1998; Roemer et al., 2001). The prognostic information enables decisions about recommended maintenance that is not required for the moment, but advantageous to perform with currently required maintenance (Mobley, 1990; Litt et al., 2000; Hess & Fila, 2002). On the basis of the diagnostic information it is possible to determine if the operation should be terminated, or if it is possible to continue operation, with or without any restrictions (see, for example, Nowlan & Heap, 1978). Decisions about operation may be based on the prognostic information, in the same way as the diagnostic information, with the advantage of a planning horizon (see, Mobley,
1990; Hess & Fila, 2002). Thereby, prognostics also enables a control of the aging of technical systems, which may be required by regulatory authorities, e.g. for nuclear power plants (Martorell et al., 1999).

As a summary, health data is necessary for making diagnoses and prognoses of a technical system’s current and future health. On the basis of the diagnostic and prognostic information it is then possible to make decisions about appropriate operation and support actions, both current and future. Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support may be seen as three interdependent methodologies. Appropriate tools should in turn support these methodologies. The combination of the methodologies and tools above may be seen as a conceptualisation of Health Management, see Figure 4. For further information, see Söderholm & Akersten (2002).

![Figure 4](image)

**Figure 4.** Health Management supported by the three methodologies Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support. These methodologies are in turn supported by different tools, of which a few examples can be found in the figure. Inspired by Söderholm & Akersten (2002).

As with most of the other approaches and concepts in this paper, there is not one definition or naming of Health Management. A lot of different descriptions and naming may be found in the literature. Mobley (1990) discusses Predictive Maintenance and Campbell & Jardine (2001) discuss Maintenance Excellence. However, Health Management is in this paper seen as something that includes both operation and maintenance, and these two activities are influenced by the actual health of the technical system. Another approach that resembles that of Health Management, as presented in this paper, is Prognostics & Health Management (PHM), which is connected to the Joint Strike Fighter developed in the USA (see, for example, Malley, 2001). A future concept, and perhaps a development of Health Management, might be Integrated Vehicle Health Management (IVHM), a concept that is under development within NASA and where the technical system is intended to perform autonomous maintenance (see, for example, Baroth et al., 2001).
MANAGEMENT FRAMEWORK

By a combination of the three management areas included in this paper a theoretical Quality Management framework supported by Requirements Management and Health Management may be outlined (see Figure 5).

![Diagram](https://via.placeholder.com/150)

**Figure 5. A theoretical Quality Management framework supported by Requirements Management and Health Management, intended to support systematic work with continuous improvements of complex technical systems in the context of dynamic stakeholder requirements.**

The stakeholders of a technical system are viewed as elements in a stakeholder system. This system is dynamic due to changes of stakeholders, their requirements, and their interrelationships. There are also a lot of different stakeholders with a diverse set of requirements. Therefore, some methodologies and tools that support a stakeholder focus are necessary, in order to manage the requirements of this dynamic system, and thereby enable stakeholder satisfaction. Several efficient methodologies and tools of this kind may be found within Requirements Management.

Since the stakeholder system is dynamic, the technical system must be changed in response to avoid stakeholder dissatisfaction. However, a number of points should be considered when a technical system is changed. A first point is the importance of availability and reliability due to the growing dependence on technical systems. A second point is safety and environmental issues, due to the serious negative effects that failures of technical systems may have on these aspects. The third point is the cost of operation and support, which has increased over the years. Hence, when a system is complex and critical, appropriate
methodologies and tools must support the continuous improvements of it, in order to avoid unwanted effects. Health Management is an approach that provides efficient methodologies and tools for this situation.

The link from the technical system to the stakeholder system is expressed by health data and information. These facts can be used to verify that some of the requirements of the stakeholders are fulfilled. The data and information may also be direct answers to some requirements of the stakeholders. There is also another, more physical, link between the stakeholder system and the technical system that is important to recognize. The operators and the technical system together form a joint system (the union of the two systems). On this level there must be a correspondence between the stakeholders’ requirements and the received data and information about the health of the technical system, in order for the operators to properly operate the technical system. However, there must also be a similar correspondence on a more aggregated level, such as the information required by regulatory authorities.

It seems quite obvious that Requirements Management and Health Management can support each other. However, as mentioned earlier, the two management approaches also strongly support some of the important core values within Quality Management. Requirements Management mainly supports the core value Stakeholder Focus, while Health Management primarily supports the core value Continuous Improvements. In addition to this, the two management approaches also both support the core value Fact Based Decisions, through the application of appropriate measurements. The facts, used to make decisions about the management of the stakeholder system and the technical system, are stakeholder requirements and health data and information, respectively.

The positive effect that a combination of Requirement Management and Health Management may have as a support to Quality Management may be realised by the reasoning by Oakland (1993) about effectiveness and efficiency. Requirements Management can be valuable for the purpose of identifying the requirements of the company’s external and internal stakeholders, in order to decide what the right things to do are (effectiveness). In order to assure that things go according to plan, i.e. to do things right (efficiency), Health Management may be valuable. The combined support from Requirements Management and Health Management to Quality Management is therefore believed to enhance both the effectiveness and the efficiency of an organisation, which will hopefully also lead toward the aim of Quality Management, i.e. to increase stakeholder satisfaction with a decreased amount of resources.

DISCUSSION

The theoretical framework presented in this paper is intended to support a systematic work with continuous improvements of complex technical systems, in the context of dynamic stakeholder requirements. The presentation of the
framework is on a rather aggregated level, but may hopefully be beneficial for a diverse set of organisations, both those that develop technical systems and those that deliver services. However, it is important to notice that an application of the framework on a more detailed level is probably strongly influenced by the environment of the specific organisation. As one example, an organisation that develops critical and very complex systems, as within the aerospace industry, will not manage requirements in the same way as an organisation that builds consumer products (see, Sommerville & Sawyer, 1997; Kotonya & Sommerville, 1998).

One reason for the fruitful synergism between the three management areas is probably the systematisation, which is strengthened by the emphasis on appropriate measurements in order to enable fact-based decisions. Fact Based Decisions is a core value that together with Stakeholder Focus and Continuous Improvements are central in the presented framework. Core values that are not directly in focus in this paper are such as Management Commitment and Employee Commitment. The reason for this is not that they are considered unimportant. On the contrary, they are seen as crucial for the actual work with continuous improvements. These complementary core values are seen as important criteria in the selection of appropriate methodologies and tools, which may probably be found within the present framework. The reason for this is that each management area has its own set of methodologies and tools, even though some can be shared between two or even three areas.

The mentioned excluded core values tied to “commitment” point out one interesting way to broaden the study by a focus on more sociological issues within the presented framework. Another exciting way to enhance the presented framework is to study more specifically how appropriate methodologies and tools can be selected, and which these methodologies and tools might be. Because of this, an application of methodologies and tools within the presented theoretical management framework has started, supported by a continued literature study. The application is directed towards a modern combat aircraft, which is considered as a highly complex and safety critical system, with stringent requirements on life cycle costs. The application is performed in close cooperation with Saab Aerospace in Linköping.

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REFERENCES


PAPER C

A MODEL FOR CONTINUOUS IMPROVEMENTS OF COMPLEX TECHNICAL SYSTEMS

ABSTRACT

Health Management is an approach that includes methodologies such as Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support. Health Management systems are intended to improve the reliability and safety of critical systems, such as aircraft and nuclear power plants. A Health Management system can also add the possibility to decrease the combined cost of operation and support throughout the whole system life cycle, which often is rather long for complex systems. However, in order to achieve and maintain reliability, safety, life cycle costs, and other requirements it is necessary to manage these, many times changing, requirements in a systemic and systematic way. This paper presents a model for continuous improvements of complex technical systems. Further on, some examples of methodologies and tools included in the model are described. A special focus is on an adapted Failure Mode & Effect Analysis (FMEA), which is function oriented and life-cost based. The model enables traceability between stakeholder requirements and critical system functions that should be covered by tools that support Condition Monitoring, Diagnostics, and Prognostics. A pilot study intended to evaluate parts of the model is described in the context of a modern combat aircraft, which is considered as a highly complex and safety critical system, with stringent requirements on low life cycle costs.

KEYWORDS

Continuous Improvements, Complex Critical Technical System, Stakeholder Requirements, System Functions, Function and Life-Cost Oriented FMEA, Condition Monitoring, Diagnostics and Prognostics

COMPLEX TECHNICAL SYSTEMS

In today’s society we are all strongly dependent on correct functions of technical systems, which have made us vulnerable to disturbances. Our vulnerability is exposed on occasions such as the mass power supply
failure in North America that affected Toronto, Ottawa, New York, Detroit, Queensland, and the states of New Jersey and Connecticut (Canada and USA, August 14, 2003). Some other, well known, examples when technical systems have failed are the accident at a nuclear power plant at Three Mile Island (USA, March 28, 1979), the leak from a chemical plant at Bhopal (India, December 23, 1984), the explosion of the space shuttle Challenger (USA, January 28, 1986), the explosion of a nuclear reactor in Chernobyl (Russia, April 26, 1986), the Concorde crash outside Paris (France, July 25, 2000), and the explosion of the space shuttle Columbia (USA, February 1, 2003).

The technical systems that surround us, and that we are dependent on, tend to increase in complexity (Juran & Godfrey, 1999). These complex technical systems often have a rather long life (see, for example, White & Edwards, 1995; Sandberg & Strömberg, 1999) For example, a combat aircraft has a life of about 30 years (Sandberg & Strömberg, 1999). During this relatively long life, the requirements on the systems’ functions will change due to the technical development, and changes in the needs of stakeholders, operational environment, laws and regulations (Bohner & Arnold, 1996; North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm & Schockert, 2003). Here a stakeholder is viewed as anyone who is affected by the system or by the process used to produce the system, today or in the future (see, the combination of discussions in North et al., 1998; Juran & Godfrey, 1999; ISO/IEC 15288).

In order to maintain a high level of stakeholder satisfaction, throughout the system’s whole life cycle, organisations responsible for the systems have to respond to changes in requirements through system evolution and continuous improvements (see North et al., 1998; Juran, 1992; Kotonya & Sommerville, 1998; Herzwurm & Schockert, 2003). Many complex technical systems of today are also critical ones with stringent requirements on safety, reliability, availability, maintainability, and security, e.g. aircraft, nuclear power plants, and spacecraft. For many complex technical systems the requirements on lower cost of operation and support throughout the system’s life cycle have also grown in importance (Moubray, 1997; Sommerville & Sawyer, 1997; Cini & Griffith, 1999; Sandberg & Strömberg, 1999; Schmidt, 2001). The latter situation has led to the development of concepts such as Life-Cycle Cost, Life-Cycle Profit, and Life-Cycle Assessment (see, for example, Blanchard, 1992; Ciambrone, 1997; Ahlmann, 2002).
When the technical system is both complex and critical it is even more important that the organisational work with stakeholder focused continuous improvements is performed in a systemic and systematic way. This is because the impact of changes becomes more difficult to understand when the complexity of systems increases (Flood & Carson, 1993; Bohner & Arnold, 1996). A modification may result in unwanted side effects and a small change in one part of the system may have a major negative impact on many other parts of the system, and also have far reaching decisive consequences (Bohner & Arnold, 1996; Sommerville & Sawyer, 1997). When the system is critical these unwanted effects may result in human death or injury, damage to, or loss of, a technical system or property, or environmental damage (MIL-STD-882C; Sommerville & Sawyer, 1997). Therefore, it seems highly important for an organisation to establish and implement an approach that identifies and handles stakeholder requirements in a proper way, at the same time as the resulting changes of the technical system are performed and controlled in a systematic way. This systemic and systematic approach for stakeholder focused continuous improvements should enable both increased stakeholder satisfaction and a reduced amount of necessary resources.

The purpose of this paper is to describe how an organisation can work with continuous improvements of complex technical system functions in the context of changing stakeholder requirements, in order to increase stakeholder satisfaction with a reduced amount of resources.

First a short description of the study approach will be outlined. Thereafter, three management approaches to continuous improvements will be described. Then, a management framework intended to support the work with continuous improvements of complex technical systems will be described. Thirdly a model that is founded on the framework will be presented. Finally, a pilot study intended to evaluate parts of the framework and the model will be presented.

STUDY APPROACH

The approach of this study may be looked upon through the four phases of the Improvement Cycle (Plan-Do-Study-Act), as described by Deming (1993). See Figure 1.

In the Plan phase it was tentatively decided what to do, how to do it, and why it should be done. However, these statements, the purpose, and research questions were slightly modified and sharpened during the
progress of the research. This was done in response to increased knowledge that was gained throughout the Do phase.

The research done in the Do phase consists mainly of a literature study and a single-case study, which were performed in parallel, in order to support each other. Empirical data was collected mainly through interviews and document studies, even though some direct observations were also made.

In the Study phase of the research process the theoretical and empirical findings were analysed. The analysis was based on a management system view as described by Hellsten & Klefsjö (2000) and Akersten & Klefsjö (2003). The results of the analysis were one management framework founded on Quality Management, Requirements Management, and Health Management (see Söderholm 2003) and a model that focused on establishing traceability between stakeholder requirements and critical

![Research Process Diagram](image_url)
system functions that should be covered by tools that support Condition Monitoring, Diagnostics, and Prognostics. A further result of the study was an adaptation of Failure mode & Effect Analysis (FMEA) in order to support the work with establishing the traceability between stakeholder requirements and critical system functions.

In the final Act phase, the contents of presented material are reviewed and some suggestions for further research are discussed. Especially the planning of a pilot study, intended to evaluate aspects of the presented model is described.

It is also important to notice that the work has been carried out in an iterative manner between the four phases, and not necessarily as functionally as it may appear in Figure 1. During the whole research continuous meetings and discussions were made with both industry and colleagues at the university.

**MANAGEMENT APPROACHES**

Both in theory and practice approaches that have been developed in order to manage the complexity and criticality of technical systems and their functions can be found (see, for example, Nowlan & Heap, 1978; Mobley, 1990; Stamatis, 1995; Moubray, 1997). At the same time one can find approaches that have been developed in order to manage changing stakeholder requirements (see, for example, Davis, 1993; Macaulay, 1996; Kotonya & Sommerville, 1998). In the stages of design and evolution of technical systems there is no clear boarder between stakeholder requirements and system functions. This is because the definition of a system is dependent upon how its boundaries are drawn, which in turn will affect the perspective. Even though one perspective is often dominant, some approaches combine the two (see, for example, Akao, 1992). However, these approaches may, on the other hand, fail to deal with the evolutionary nature of complex systems (Herzwurm & Schockert, 2003). Therefore, the work with continuous improvements of complex technical systems can probably benefit from a combination of appropriate approaches with perspectives that emphasise requirements or functions.

There are different views on management approaches. A system view on management approaches is described by Hellsten & Klefsjö (2000) and Akersten & Klefsjö (2003). Elements of these management systems are core values, methodologies, and tools.
The core values constitute a very important element as they are the basis of the culture of the organisation and also the basis of goals set by the organisation. Another element of the management system is the set of methodologies, which are ways of working in the organisation to reach the goals. A few examples of methodologies are Quality Function Deployment (QFD), Failure Mode & Effect Analysis (FMEA), and Risk Analysis. The third element in the management system consists of tools that are rather concrete and well-defined. Sometimes these tools have a statistical basis, to support decision-making or facilitate the analysis of data. Some tools that support the methodologies mentioned above are the House of Quality (HoQ), FMEA-sheets, and Fault Trees. (See Hellsten & Klefsjö, 2000; Akersten & Klefsjö, 2003)

Some examples of management approaches that are used to maintain and improve technical systems are Quality Management, Requirements Management, and Health Management. The first approach, Quality Management, emphasises continuous improvements that are initiated by stakeholder requirements (which are expressed as needs, wants, desires, expectations, and perceived constraints), and supported by performed measurements (see, for example, Shewhart, 1931; Juran, 1992; Deming, 1993). Requirements Management is an approach that includes methodologies and tools for the management of dynamic stakeholder requirements throughout the technical system’s whole life cycle (see, for example, Davis & Leffingwell, 1996; Macaulay, 1996; Kotonya & Sommerville, 1998; Söderholm, 2003). The third approach, Health Management, can be applied in order to improve the safety and reliability of technical systems, and also to decrease the combined cost of operation and support throughout the system’s life. This is achieved through the application of tools, such as sensors and Artificial Intelligence, which support methodologies, such as, Condition Monitoring, Diagnostics, and Prognostics (see, for example, Mobley, 1990; Becker et al., 1998; Litt et al., 2000; Baroth et al., 2001; Campbell & Jardine, 2001; Dunne et al., 2001; Hess & Fila, 2002; Söderholm & Akersten, 2002; Söderholm, 2003).

FRAMEWORK FOR CONTINUOUS IMPROVEMENTS

By a combination of the three studied management areas Quality Management, Requirements Management, and Health Management a theoretical management framework, based on the management system view as described by Hellsten & Klefsjö (2000) & Akersten & Klefsjö (2003), has been outlined by the author, see Figure 2. This framework is originally presented in Söderholm (2003).
The positive effect that a combination of Requirement Management and Health Management may have as a support to Quality Management can be realised in terms of the reasoning by Oakland (1993) about effectiveness and efficiency. Requirements Management may be valuable for identifying the requirements of the company’s external and internal stakeholders, in order to decide what the right thing to do is (effectiveness). In order to assure that things go according to plan, i.e. to do things right (efficiency), Health Management may be valuable. The combined support by Requirements Management and Health Management of Quality Management is therefore believed to enhance both the effectiveness and the efficiency of an organisation. This will hopefully also lead toward the aim of Quality Management, i.e. to increased stakeholder satisfaction with a decreased amount of resources (see Hellsten & Klefsjö, 2000).

The core value System View is fundamental in the framework and is applied in order to describe a stakeholder system (Checkland, 1999; Juran, 1992), a technical system (Hubka, 1982), and a joint system consisting of
both man and machine (Hollnagel et al., 1995; Blanchard, 2001). The three management approaches are also related to these three systems to different extents. On a conceptual level the management framework indicates how an organisation can work with continuous improvements of functions related to complex technical systems.

The stakeholders of the technical system are viewed as elements in a stakeholder system. This system is dynamic due to changes of stakeholders, their requirements, and their interrelationships. There are also a lot of different stakeholders with a diverse set of requirements. Therefore, some methodologies and tools that support a stakeholder focus are necessary, in order to manage the requirements of this dynamic system, and thereby enable stakeholder satisfaction. This satisfaction depends on the fulfilment of stakeholder requirements related to areas such as reliability, availability, safety, environmental issues, life cycle cost, and performance. Several efficient methodologies and tools for this purpose may be found within Requirements Management. (Söderholm, 2003).

To support continuous improvements of complex technical systems Health Management is believed to be a valuable approach. The rationale for selecting Health Management as a support to Quality Management may be found in the description made by Moubray (1997), who describes a number of important stakeholder requirements. A first point is the growing dependence on technical systems, which has led to reliability and availability having become more important. A second point is the awareness of safety and environmental issues, due to the serious negative effects that failures of technical systems have on these issues. The third point is the cost of operation and support of technical systems, which historically have increased over the years. Health Management is an approach that can improve the reliability and safety of a critical technical system, and also reduce the combined cost of operation and support throughout the life of the technical system (see, for example, Mobley, 1990; Becker et al., 1998; Litt et al., 2000; Baroth et al., 2001; Campbell & Jardine, 2001; Dunne et al., 2001; Hess & Fila, 2002; Söderholm & Akersten, 2002; Söderholm, 2003). Hence, when a system is complex and critical, appropriate methodologies and tools must support the continuous improvements of it, in order to avoid unwanted effects. Health Management is an approach that provides efficient methodologies and tools for this situation.

The link from the technical system to the stakeholder system is expressed by system functions. These functions are monitored and communicated to
the stakeholders as health data and information. This data and information act as facts and may be used to verify that some of the requirements of the stakeholders are fulfilled. The data and information may also be direct answers to some requirements of the stakeholders. There is also another, more physical, link between the stakeholder system and the technical system that is important to recognize. The operators and the technical system together form a joint system, the union of the two systems, as described by Hollnagel et al. (1995). On this level there must be a correspondence between the stakeholders' requirements and the received data and information about the health of the technical system, in order for the operators to be able to properly operate the technical system. However, there must also be a similar correspondence on a more aggregated level, such as the information required by regulatory authorities. (Söderholm, 2003)

Based on the description made above, the present writer strongly believes that Requirements Management and Health Management can support each other. However, as mentioned earlier, the two management approaches also strongly support some of the important core values within Quality Management. Requirements Management mainly supports the core value Stakeholder Focus, while Health Management primarily supports the core value Continuous Improvements. In addition to this, the two management approaches also both support the core values System View and Fact Based Decisions. The latter fact is supported through the application of appropriate measurements. The facts used to make decisions about the management of the stakeholder system and the technical system is stakeholder requirements and health data and information, respectively. (Söderholm, 2003)

A technical system is seen as an artificial deterministic system that produces the effects necessary to achieve the transformation of operands, as discussed by Hubka (1982). The complexity of a (technical) system increases with the number of elements and the attributes and number of interrelationships between these elements (Flood & Carson, 1993). Health Management is believed to be especially valuable when the technical system of interest is a complex one. This is because Health Management enables abstraction and decomposition of the system, which is necessary in order to understand a complex system (Törne, 1996). Health data and information are measurements that represent the actual health, or appropriate indicators of the health, of a technical system, as discussed in Mobley (1990) and Campbell & Jardine (2001). It may be of interest to note that Requirements Management can probably also support the
management of technical complexity (Davis & Leffingwell, 1996). The health data is necessary to make diagnoses and prognoses of a system’s current and future health. On the basis of the diagnostic and prognostic information it is then possible to make decisions about appropriate operation and support actions, both current and future. Here Condition Monitoring, Diagnostics & Prognostics, and Condition Based Operation & Support may be seen as three interdependent and suitable methodologies. These methodologies are in turn supported by appropriate tools.

The maintenance action or operation change is a response to a failure. The definitions of potential and functional failure made by Nowlan & Heap (1978) are used in this paper. The failure is seen as an unsatisfactory condition that may be a real inability to perform a necessary function (diagnostics), or a judgement, based on physical evidence, that it will soon be unable to perform such a function (prognostics). A functional failure is the inability of a system to meet a specified performance standard (diagnostics). A potential failure is an identifiable physical condition which indicates that a functional failure is imminent (prognostics). A potential failure is thus one, which is related to the fact that the system will, within a short period of time, develop a functional failure. The failure concept discussed by Nowlan & Heap (1978) is in line with the one discussed by Lyytinen & Hirschheim (1987) and Zeithaml et al. (1990), where a failure is seen as a gap between some existing situation and a desired situation for the members of a particular stakeholder group. It seems logical to draw on the presented failure concepts and connect them to the stakeholder concept, by using the discussion about the multidimensional and dynamic nature of quality made by Garvin (1988) and North et al. (1998).

Garvin (1988) points out that it is beneficial to be aware of different approaches to quality. In order to support this awareness of different quality approaches a stakeholder focus seems appropriate, which may probably be achieved with the aid of Requirements Management. Requirements Management is seen as a systematic approach to eliciting, organising, documenting, and managing both the initial and the changing requirements of a technical system, as discussed by Davis & Leffingwell (1996). It is also believed that Health Management can support the validation of requirements, and thereby contribute to the management of requirements. User-based definitions of quality are founded on the premise that quality lies in the eyes of the beholder, and that the products that best satisfies the consumer preferences is of the highest quality (Garvin, 1988). Initially it may be favourable to have a user-based approach, when identifying the requirements that the market has. At the design stage a
product-based approach can be used in order to deploy desired characteristics into specifications. A production-based view on quality is beneficial to apply in the production, in order to fulfil requirements and standards and thereby avoid cassation. Based on the reasoning about human activity systems made by Checkland (1999), stakeholders of a technical system are considered elements in a stakeholder system. The interrelationship between the stakeholders and between the stakeholders and the technical system are expressed by requirements. (Söderholm, 2003)

**PROCESSES FOR CONTINUOUS IMPROVEMENTS**

The analysis of identified processes in the case study was based on the management system view of Quality Management and the constructed management framework. The focus of the analysis was on processes that included methodologies and tools for the management of stakeholder requirements and system functions, and how these were interrelated.

The identified processes may be summarised in the three processes Product Development, Integrated Logistics Support, and System Safety & Reliability. The product development process includes the design of both the technical system and the support system. This approach is natural since the stakeholders external to the developing organisation are interested in the functions of the product (the combination of the technical system and the support system) and less interested in where the functions are realised. However, in this paper the focus is on the technical system and its functions, and the elements of the support system are seen as stakeholders of the technical system. The interface between the technical system and the support system is manifested by health data and information received from the part of the technical system that is related to Health Management. This part of the technical system consists of the methodologies Condition Monitoring, Diagnostics & Prognostics, and supporting tools such as sensors and Artificial Intelligence (Söderholm & Akersten, 2002). Hence, the three integrated processes may be seen as one Technical System Development Process, one Integrated Logistics Support Process, and one System Safety & Reliability Process. The input to the processes is stakeholder requirements and the output from the processes is critical functions that should be covered by tools from Health Management. See Figure 3.
Figure 3 Three interrelated processes that support the work with continuous improvements by providing traceability between stakeholder requirements and system functions that should be covered by tools from Health Management.

**METHODOLOGIES AND TOOLS FOR CONTINUOUS IMPROVEMENTS**

Within the three management approaches included in the management framework and the three identified processes a number of methodologies exist. The selection and combination of appropriate methodologies were mainly based on the core values in Quality Management that were in focus in the study. However, an awareness of other core values of Quality Management also contributed to the selection of appropriate methodologies. The four fundamental core values that the methodologies should support were Continuous Improvements, Stakeholder Focus, Fact Based Decisions, and System View, which was indicated by the literature study. Other core values that were also considered were Everybody’s Participation and Process View, which is described in the literature and that emerged as important also in the case study.

The four existing and widely, often successfully, applied methodologies are Quality Function Deployment (QFD), Failure Mode & Effect Analysis (FMEA), Reliability-Centred Maintenance (RCM), and Safety & Reliability Analysis (SRA) founded on the description in MIL-STD-882C.

One main reason for this selection is that the methodologies emphasise either stakeholder requirements or system functions, even though the other
aspect always is present in some way, for example as decision criteria. See Figure 4.

![Diagram of interrelationship between methodologies]

**Figure 4** The interrelationship between some methodologies that are related to each other in order to enable traceability between stakeholder requirements and system functions.

The proposed combination of methodologies is intended to enable traceability between stakeholder requirements and system functions. This traceability is seen as the key to successful work with continuous improvements of complex technical systems. The reason for this is that the effects and consequences of proposed changes can be “predicted” through the application of the proposed methodology in the “requirements domain”. The prediction can later on be verified through the collection of health data and information, which should reflect system functions that correspond to stakeholder requirements in the “functions domain”. Proposed changes may also originate in the evaluation of monitored functions, if it is discovered that the requirements of stakeholders are not fulfilled, through diagnostics or prognostics activities.

The perspective in QFD is founded on the stakeholder view and sets out to transfer these into corresponding system functions. FMEA, RCM, and SRA have a perspective influenced by the prevention or reduction of failure of system functions, which is identified through stakeholder requirements. The combination of aspects from the four mentioned methodologies above should enable a strong connection between stakeholder requirements and system functions. The choice of the word “requirement” or “function” is more due to whether the perspective originates from the stakeholders or
the system. Another common strength in the methodologies is the combination of both a systemic and a systematic approach.

The reason for selecting RCM and the specific SRA, was mainly based on findings in the case study. These two methodologies are common in the aerospace industry all over the world, and have also proved to be successful. Here it should be noticed that RCM is called MSG-3 (Maintenance Steering Group 3) in the aerospace industry and RCM outside the aerospace industry. RCM mainly focuses on maintenance issues, while the SRA mainly focuses on safety and reliability aspects, even though they partly cover each other also in these aspects. The literature study also corroborated these empirical findings. In both these methodologies FMEA may be applied. However, even if the stakeholder requirements are the foundation for the work with the three methodologies mentioned above, the focus is on system functions. In order to emphasise more strongly the aspect of stakeholder requirements some additional methodology seems necessary to be included. According to Macaulay (1996), QFD is a common methodology when a Quality Management approach is adapted to the management of stakeholder requirements. The idea of combining QFD, FMEA, and Fault Tree Analysis (FTA) is described also by Akao (1992), who applies the latter two for “reliability deployment”.

Stamatis (1995) describes how QFD and FMEA complement each other. Both methodologies aim at continuous improvements, stakeholder satisfaction, and the reduction of failures. However, they cannot replace each other since QFD gives input to the FMEA.

Many descriptions of RCM emphasise the fundamental importance of FMEA. For instance, Nowlan & Heap (1978) state that the FMEA-sheet can be used in combination with operator experiences in order to identify functions which are necessary to analyse further. Moubray (1997) also describes the importance of the result of the FMEA as input to the RCM Decision Diagram.

In MIL-STD-1629A (p. iii) it is stated that although the FMEA is an essential reliability task, it also provides information for other purposes. Some situations that are regarded as appropriate for the FMEA are maintainability considerations, safety analysis, logistics support analysis, and the design of subsystems for failure detection and isolation. One example of where the FMEA is mentioned as an appropriate support, in
order to determine the optimal design of an on-board level BIT, is MIL-STD-1591.

In the references above the importance of the FMEA and its connection to the three other methodologies may be seen. Therefore, the FMEA is considered as a central methodology that connects and summarises information from the other three methodologies. See Figure 4.

Quality Function Deployment

Akao (1992) describes QFD as a methodology that ensures quality throughout each stage of the product development process, starting with design. The aim of QFD is to satisfy the stakeholders by transferring the requirements of the stakeholders into design targets and major quality assurance measures to be used throughout the production stage (Akao, 1992).

Slabey (1990) states that QFD translates stakeholder requirements into appropriate organisational requirements at each stage from research and product development through engineering and manufacturing and marketing, sales, and distribution.

Bergman & Klefsjö (2003) state that QFD is an excellent methodology for supporting communication and participation, and accordingly the core value Everybody’s Participation. This is because QFD requires cross-functional teams to meet and work out common concepts, and it provides a common basis necessary for integrated product development.

Experiences have shown that QFD has reduced by half the problems previously encountered at the initial stages of product development and has reduced development time by one-half to one-third, while also ensuring stakeholder satisfaction and increasing sales. However, if QFD is applied incorrectly it may increase work without achieving the potential benefits. (Akao, 1992)

The central tool that QFD is founded on is different versions of the Matrix Diagram, of which the House of Quality probably is the best-known (Akao, 1992). Other tools that may be a support in the work with requirements are standards such as IEEE STD 610.12, ANSI/IEEE STD 830, and IEEE STD 830.
Failure Mode & Effect Analysis

Failure Mode & Effect Analysis is a very useful methodology for reliability analysis. Some examples of applications of FMEA are rough qualitative analyses initiated during planning and design, a more detailed and quantitative analysis during design and development, and for pre-production engineering. (Bergman & Klefsjö, 2003)

The FMEA is an engineering methodology that is applied in order to define, identify, and eliminate known and potential deviations from a process or a product before they reach the stakeholders. Hence the aim of FMEA is to maximise the satisfaction of the stakeholders by eliminating and reducing known or potential deviations. The FMEA is alive, updated continually, and never really completed. Hence, FMEA is a true dynamic methodology for continuous improvements. (Stamatis, 1995)

The FMEA should be initiated as an integral part of the early design of a system and should be updated to reflect design changes. FMEA should also be a major consideration at each design review, from the first preliminary one to the final design. Hence, the FMEA must be iterative and reflect the design process. If the work is appropriately performed it can be useful and effective in order to supporting and improving both system design and decision making. (MIL-STD-1629A)

The FMEA is a methodology that requires a cross-functional and multidisciplinary team. The FMEA cannot be done on an individual basis. The team must be defined as appropriate for a specific situation and cannot serve as a universal FMEA team in an organisation. (Stamatis, 1995)

The FMEA should start as soon as possible, even when all the facts and information are not known. The FMEA starts when a new process or product is designed, when a new application is found for the process or product, and when improvements are considered for an existing process or product. (Stamatis, 1995)

Any FMEA conducted properly and appropriately will provide the practitioner with useful information that may reduce the risk and work load related to the unit of analysis. This is because the FMEA is a logical and progressive potential failure methodology that allows the task to be performed more effectively. (Stamatis, 1995)

The methodology of FMEA is in many studied sources considered synonymous with the FMEA-sheet. However, in this paper the FMEA-sheet
is seen as a supporting tool of the FMEA, which is a methodology. Another tool that supports this work is MIL-STD-1629A.

Reliability-Centred Maintenance
Reliability-Centred Maintenance is a methodology for the development of scheduled maintenance, with the aim of realising inherent reliability capabilities of the system at minimum cost. The resulting scheduled maintenance includes all tasks necessary to protect safety and operating reliability, and only the tasks that will accomplish this objective. (Nowlan & Heap, 1978)

The system is partitioned in order to identify Maintenance Significant Items (MSIs). In order to support this work a Decision Diagram that resembles a tree-diagram is applied as a supporting tool. See Nowlan & Heap (1978).

The decision diagram logic is also applied in order to decide if the maintenance task is cost-effective. The cost-effectiveness is only considered for maintenance tasks that are related to uncritical failures. In this case aspects such as failure-rate, operational consequences, unusual high repair or operating costs are considered. The logic for the Decision Diagram is also useful in order to decide upon feasible product improvements. (Nowlan & Heap, 1978)

The Decision Diagram of RCM that seems appropriate to apply is the one described by Moubray (1997). The main rationale for this choice is the systematic inclusion of failures that could affect the environment. However, Nowlan & Heap (1978) also describe Decision Diagrams for evaluating cost-effectiveness and deciding upon reasonable product improvements. The inclusion of failures with possible environmental effects brings the classification of failures within RCM closer to the one mentioned in MIL-STD-882C. However, the categorisation of “hidden” and “evident” failures, as emphasised in RCM adds a further dimension to the classification of failures, compared to the one in MIL-STD-882C.

Instead of the Decision Diagram within RCM it may be beneficial to adapt special Event Trees that support the FMEA.

Some benefits that may be achieved with RCM are (Moubray, 1997):

- Greater safety and environmental integrity.
- Improved operating performance.
- Greater maintenance cost-effectiveness.
• Longer useful life of expensive items.
• A comprehensive database.
• Greater motivation of individuals.
• Better teamwork.

The main Decision Diagram as presented by Moubray (1997) includes a number of questions that may be answered by “yes” or “no”. Every chain of answers results in a recommended task to perform in order to design the appropriate maintenance of a system. The Decision Diagram is hence applied in order to classify failures and find appropriate countermeasures for each category of failures. The first level questions cover failure consequences such as if the failure is hidden or evident, if it affects safety, has environmental implications, or interferes with operational capability, see Table 1. The next level of questions covers aspects of multiple failures, available technology, and economy. This level of questions is applied in order to document whether a proactive task has been selected, and if so, what type of task.

Table 1 Classification of functions and their failure according to Moubray (1997).

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evident or Hidden</td>
<td>Evident: A failure of the function will on its own eventually become inevitably evident to the operators under normal circumstances.</td>
</tr>
<tr>
<td></td>
<td>Hidden: A failure of the function will not become evident to the operators under normal circumstances if it occurs on its own.</td>
</tr>
<tr>
<td>Safety</td>
<td>If the failure mode results in a loss of function or other damage which may injure or kill someone.</td>
</tr>
<tr>
<td>Environment</td>
<td>If the failure mode results in a loss of function or another damage which may lead to the breach of any known environmental standard or regulation.</td>
</tr>
<tr>
<td>Operation</td>
<td>A failure of the function has a direct adverse effect on operational capability (output, quality, customer service, or operating costs in addition to the direct cost of repair).</td>
</tr>
</tbody>
</table>

The result of the RCM analysis is an appropriate action for each failure, the time intervals for the actions, and who is responsible for the action. The
different types of action that may be the outcome of the RCM analysis are (Moubray, 1997):

- **Scheduled on-condition task.** A suitable on-condition task could be found to anticipate the failure in time to avoid the consequences.
- **Scheduled restoration task.** A scheduled restoration task could be found in order to prevent the failures.
- **Scheduled discard task.** A suitable scheduled restoration task could be found in order to prevent the failures.
- **Scheduled failure-finding task.** This task is only concerned with hidden failures, which by definition may result in multiple failures. The task is selected if it is possible to do the task and it is practical to do it at the required frequency, at the same time as it reduces the risk of multiple failures to an acceptable level.
- **Compulsory redesign.** The failure is serious enough to warrant redesign, due to that it affects safety or the environment.
- **No scheduled maintenance.** A deliberate decision has been taken to let failure happen, due to the fact that consequences are purely economic and no suitable preventive task has been found. However, in this situation the next, and last, task should be considered.
- **Redesign may be desirable.** Even though it has been decided that no preventive action is taken, redesign may be desirable.

The FMEA-sheet is a central tool for supporting RCM. Another tool is the Decision Diagram. See, for example, Nowlan & Heap (1978) and Moubray (1997). Another tool that may support the work with RCM is MIL-STD-2173(AS). For a thorough discussion about issues related to the implementation of RCM see Backlund (2003).

### Safety & Reliability Analysis

There are a vast number of different methodologies for system safety analysis and management. The one selected for the purpose of this study is the one described in MIL-STD-882C. The reason for this selection is that the standard is applied in the studied case, where it has proved to be valuable. The standard itself is seen as a supporting tool in the analysis work related to safety and reliability. Other tools that support this work are documents such as MIL-STD-756B, MIL-STD-882D, and RTCA/DO-178B.

System safety engineering draws upon professional knowledge and specialised skills in the mathematical, physical, and related scientific disciplines, together with the principles and methods of engineering design and analysis for specifying, predicting, and evaluating the safety of the
system. The degree of safety achieved in a system is directly dependent on the emphasis given and applied during all phases of the life cycle. Safety, consistent with mission requirements, should be designed into the system in a timely and cost-effective manner. The criticality of failures is classified in MIL-STD-882C according to four categories. These categories are catastrophic, critical, marginal, or negligible, see Table 2. (MIL-STD-882C)

In order to prioritise actions a matrix that combines criticality and frequency can be used. The frequencies are classified as frequent, probable, occasional, remote, or improbable, see Table 3. The matrix design assigns a different index to each criticality-frequency pair thus avoiding the situation caused by creating indices as products of numbers assigned to criticality and frequency. A situation where the product of criticality and frequency gives the same result hides information pertinent to prioritisation, see Table 4. (MIL-STD-882C)

Table 2: Classification of severity of function failure according to MIL-STD-882C.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>Death, system loss, or severe environmental damage.</td>
</tr>
<tr>
<td>Critical</td>
<td>Severe injury, severe occupational illness, major system or environmental damage.</td>
</tr>
<tr>
<td>Marginal</td>
<td>Minor injury, minor occupational illness, or minor system or environmental damage.</td>
</tr>
<tr>
<td>Negligible</td>
<td>Less than minor injury, occupational illness, or less than minor system or environmental damage.</td>
</tr>
</tbody>
</table>

Table 3: Probability levels and their description on individual items and fleet or inventory, according to MIL-STD-882C.

<table>
<thead>
<tr>
<th>PROBABILITY</th>
<th>SPECIFIC INDIVIDUAL ITEM</th>
<th>FLEET OR INVENTORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent</td>
<td>Likely to occur frequently.</td>
<td>Continuously experienced.</td>
</tr>
<tr>
<td>Probable</td>
<td>Will occur several times in the life of an item.</td>
<td>Will occur frequently.</td>
</tr>
<tr>
<td>Occasional</td>
<td>Likely to occur some time in the life of an item.</td>
<td>Will occur several times.</td>
</tr>
<tr>
<td>Remote</td>
<td>Unlikely but possible to occur in the life of an item.</td>
<td>Unlikely but can reasonable be expected to occur.</td>
</tr>
<tr>
<td>Improbable</td>
<td>So unlikely that it may be assumed occurrence may not be experienced.</td>
<td>Unlikely to occur, but possible.</td>
</tr>
</tbody>
</table>
In MIL-STD-882C an order of precedence for satisfying system safety requirements and resolving identified hazards may be found. A hazard is defined as a condition that is a prerequisite of a mishap. A mishap is, in turn, defined as an unplanned event or series of events that results in death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment. The priority order is as follows (MIL-STD-882C):

- **Design for minimum risk.** The first priority is to design in order to eliminate hazards. If an identified hazard cannot be eliminated, reduce the associated risk to an acceptable level.
- **Incorporate safety devices.** If identified hazards cannot be eliminated or their associated risk adequately reduced through design selection, that risk should be reduced to an acceptable level through the use of fixed, automatic, or other protective safety design features or devices. Provisions should be made for periodic functional checks of safety devices when applicable.
- **Provide warning devices.** When neither design nor safety devices can effectively eliminate identified hazards or adequately reduce associated risk, devices should be used to detect the condition and to produce an adequate warning signal to alert personnel of the hazard.
- **Develop procedures and training.** Where it is impractical to eliminate hazards through design selection or adequately reduce the associated risk with safety and warning devices, procedures and training should be used. This solution may not be used as the only one when the hazard is classified as catastrophic or critical.

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Catastrophic</td>
</tr>
<tr>
<td>Frequent</td>
<td>1</td>
</tr>
<tr>
<td>Probable</td>
<td>2</td>
</tr>
<tr>
<td>Occasional</td>
<td>4</td>
</tr>
<tr>
<td>Remote</td>
<td>8</td>
</tr>
<tr>
<td>Improbable</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hazard Risk Index</th>
<th>Suggested Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-5</td>
<td>Unacceptable</td>
</tr>
<tr>
<td>6-9</td>
<td>Undesirable</td>
</tr>
<tr>
<td>10-17</td>
<td>Acceptable with review</td>
</tr>
<tr>
<td>18-20</td>
<td>Acceptable without review</td>
</tr>
</tbody>
</table>

Table 4 Example of a Risk Assessment Matrix. From MIL-STD-882C.
Cross-Functional Teams
Each of the four methodologies identified in the analysis emphasise the importance of cross-functional teams. This is also something that has been discovered in the case study, where emphasis on the participation of different expertise and knowledge is considered vital, due to the complexity and criticality of the technical system. Another discovery in the case study was that all documents had to be approved by someone else than the original author. This procedure is followed in order to secure that the documents are correct. At the same time someone else than the author of the document participates in the work. The documents are often approved by someone in a managerial position. In this way the management also has to be committed.

The identified emphasis on cross-functional teams and the procedure of approved documents support core values of Quality Management such as Management Commitment and Everybody’s Participation.

Based on the findings described above, the present writer thinks that it is most valuable to add the methodology of Cross-Functional Teams to the other four methodologies QFD, RCM, FMEA, and SRA.

MODEL FOR CONTINUOUS IMPROVEMENTS
The methodologies and tools that have been described in this paper may be conceptualised in a summary holistic model for continuous improvements. However, the present writer also thinks that it is necessary to include the methodologies and tools that are included in Health Management, in order to close the loop and enable continuous improvements with the aid of collected health data and information (see Söderholm & Akersten, 2002).

It may also be beneficial to include the core values that have been the basis of the research, but also those identified as vital during the research. See Figure 5.
Figure 5 A holistic model for continuous improvements of complex and critical technical systems. The model includes suggestions for methodologies and tools from Requirements Management and Health Management that together support the core values of Quality Management, in order to reach the aim of increased stakeholder satisfaction with a reduced amount of resources.

ADAPTED TOOLS FOR CONTINUOUS IMPROVEMENTS

Some of the tools that support the selected methodologies have been combined and adapted to the context of the study. This means that the tools have been directed toward the aim of achieving traceability between stakeholder requirements and critical system functions that should be covered by tools within Health Management.

Matrix Diagram
The Matrix Diagrams of QFD is adapted to the purpose of this study. The result of the adaptation is three successive diagrams. The first diagram shows the correlation within stakeholders, the correlation within requirements, and the relationship between stakeholders and requirements. The second diagram shows the correlation within stakeholder requirements, the correlation within system functions, and the relationship between stakeholder requirements and system functions. The third diagram shows the relationship between system functions and subsystem functions, and the correlation within each set of functions. See Figure 6.
Figure 6 Matrix Diagrams that can be applied in order to deploy stakeholder requirements to corresponding subsystem functions, in order to achieve requirement traceability.

FMEA-Sheet
The FMEA-sheet is a central tool in all the selected methodologies that are identified and combined in the analysis. However, the FMEA-sheet has by the present writer been extended and adapted to the purpose of this study. This version of the FMEA-sheet may be seen in Table 5. The fields of the FMEA-sheet also cover the activities that may be included in the FMEA work. However, it should be noticed that not all fields have to be covered in all analyses. The purpose of the analysis is decisive for which fields to cover. The work with the FMEA starts at the system level and can be
deployed down to an appropriate subsystem level. The FMEA-sheet works as a tool for documentation, communication, and cooperation.

**Table 5** Suggested fields that should be included in the FMEA-sheet in order to support the work with continuous improvements of complex technical systems.

<table>
<thead>
<tr>
<th>NUMBER</th>
<th>DESIGNATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Definition of the System and its Relation to other Systems</td>
</tr>
<tr>
<td>1</td>
<td>Function/Requirement</td>
</tr>
<tr>
<td>2a</td>
<td>Functional Failure (Loss of Function), Unfulfilled Requirement (Fault)</td>
</tr>
<tr>
<td>2b</td>
<td>Failure Mode (Fault Mode)</td>
</tr>
<tr>
<td>3</td>
<td>Failure Effect (a Group of Fields in the Sheet)</td>
</tr>
<tr>
<td>3a</td>
<td>Effect on Analysed System</td>
</tr>
<tr>
<td>3b</td>
<td>Effect on Neighbouring Systems</td>
</tr>
<tr>
<td>3c</td>
<td>Effect on Superior System</td>
</tr>
<tr>
<td>4</td>
<td>Existing Management or Control</td>
</tr>
<tr>
<td>5</td>
<td>Possible Causes of the Functional Failure, or the Failure (Fault) Mode</td>
</tr>
<tr>
<td>6</td>
<td>Actions against Failures, or Consequences (Risk Reduction)</td>
</tr>
<tr>
<td>7</td>
<td>Actions at Failures</td>
</tr>
<tr>
<td>7a</td>
<td>Detection of Failure</td>
</tr>
<tr>
<td>7b</td>
<td>Failure Localisation (Fault Localisation)</td>
</tr>
<tr>
<td>7c</td>
<td>Corrective Actions</td>
</tr>
<tr>
<td>7d</td>
<td>Resource Needs</td>
</tr>
<tr>
<td>8</td>
<td>Foundation for Prioritisation</td>
</tr>
<tr>
<td>8a</td>
<td>The Frequency of the Failure Mode</td>
</tr>
<tr>
<td>8b</td>
<td>Conditional Probability for stated Consequence or Scenarios.</td>
</tr>
<tr>
<td>8c</td>
<td>Valuation of stated consequence</td>
</tr>
<tr>
<td>9</td>
<td>Decisions</td>
</tr>
<tr>
<td>9a</td>
<td>Responsible for Measures</td>
</tr>
<tr>
<td>9b</td>
<td>Concrete Proposal for Measures</td>
</tr>
<tr>
<td>9c</td>
<td>Receipt of Performed Measure and Modified Analysis</td>
</tr>
</tbody>
</table>

Kacprzynski et al. (2001) list some points that should be considered when working with FMEA in order to design a Health Management system. As a
first point it is important to address the precursors or symptoms to failure modes. Another point that should be considered is the sensors and the placement of these in order to observe failure mode symptoms or effects. It is further necessary to address tools that support Diagnostics and Prognostics. A fourth point is that is necessary to focus on the combination of subsystems and the interface between them in order to avoid an excessive amount of sensors.

Of the four points listed by Kacprzynski et al. (2001), the FMEA in this paper focus on the first and last ones. This is because these points focus on what functions to cover and why. The two other points focus on how the system should be designed, which not is considered in this paper. However, it is possible to extend the suggested FMEA in order to also address these points. This extension would be beneficial in the more detailed design of the Health Management system.

The Scenario-Based and Life Cycle Cost oriented FMEA presented by Kmenta & Ishii (2000) has a strong influence on the thought described in this paper.

Short descriptions of the different steps found in Table 5 are presented in the following text.

Number 0: Definition of the System and its Relation to other Systems
The system (subsystem, component, item, process phase, task) that is analysed should be stated. The relationship between the analysed system and other systems in its environment will be mapped and clarified. This can be done by using terms such as: “the system is affected by ....”, and “the system affects ...”

When the FMEA is concerned with a technical system the block diagram is a tool that can be applied as a supporting tool. If the improvement effort is concerned with a process the process flowchart may be a more appropriate tool. (Stamatis, 1995).

Number 1: Function/Requirement
The functions of the system and the requirements on the system are identified with an open mind. In this stage the identification of requirements is crucial and a list of different stakeholders should be able to give some inspiration. This list and correlation of stakeholder are the same as the input in matrix diagram one of the QFD approach. See Figure 6.
The correspondence between stakeholder requirements and system functions may probably be clarified through an approach that is influenced by QFD. The valuable support available here are the matrix diagrams and not the extensive numerical exercises that is included in a thorough QFD. The input to this step is summarised in matrix diagram number two of the QFD approach.

It may also be beneficial to apply brainstorming as a methodology in this step (Stamatis, 1995).

**Number 2a: Functional Failure, unfulfilled Requirement**
A failure is defined as "an unsatisfactory condition". This unsatisfactory condition is related to stakeholder requirements. The stakeholder requirements are listed and correlated in matrix diagram one of the QFD approach. The stakeholder requirements and corresponding system functions are listed in matrix diagram two. A functional failure is the inability of a function to meet a specified performance standard. A potential failure is an identifiable physical condition which indicates that a functional failure is imminent.

**Number 2b: Failure Mode**
A failure mode is the way in which the functional failure or unfulfilled requirement is manifested. There is here is an obvious risk that limitations of a standard list of failure modes are applied, more or less connected to failure causes. Traditional design-FMEAs often focus on failure causes and for this reason the completeness often suffers.

From a system view it is important to focus on the failure causes that may be initiated by functional failures in other systems. These systems have been mapped in step 0.

When applying the FMEA in order to design a Health Management system it is important to address the precursors or symptoms of failure modes, both on system and component level. Failure mode symptoms that occur prior to failure are these indications. (Kacprzynski et al., 2001)

**Number 3: Failure Effect**
What happens when the system fails? The worst credible mishaps as well as less catastrophic scenarios are described.

- *Effect on the Analysed System.* The way in which the failure is manifested. The information here may be connected to failure detection, and thereby be valuable in the localisation of faults (FL).
• **Effects on Neighbouring Systems.** Other neighbouring systems can be affected by the analysed one. Three types of proximity may be considered: Functional, Information, and Physical. When the proximity is due to function and information both functional failures and potential failures should be considered. When the proximity is due to physical aspects it is primarily functional failures that are considered.

• **Effect on Superior System.** The effect on a superior system may either be direct due to functional failure of the analysed system, or indirect through functional failure of an affected neighbouring system.

**Number 4: Existing Management or Control**
Here a completion of the descriptions of different scenarios related to possible failure effects are made. Different scenarios are followed up by different descriptions of management and control. Different kinds of management and control can result in different effects.

**Number 5: Possible Cause to the Functional Failure or Failure Mode**
Depending on whether if the analysis is made on an overarching system level, where only functional failures are included, or whether the analysis is made on a more detailed level, the identification of possible causes gets more or less profound.

It is important that the identification of possible causes is made in detail only when this is called upon through the severity of the failure effect, or by a very high failure frequency.

**Number 6: Actions against Failures, or Consequences**
Starting from possible causes ideas for possible countermeasures may be noted. The first choice is to prevent occurrences of failures, and the second choice is to reduce consequences.

**Number 7: Actions at Failures**
Both functional failures (faults) and potential failures (failures) should be considered.

• **Detection of Failure.** The way in which a failure is detected should be identified. Existing means of assistance, such as FM/RM & BIT systems, should be presented.

• **Fault Localisation.** The means of assistance that are available should be presented. One example is a system for FM/RM & BIT, if it is useful in the localisation of faults.
• **Corrective Actions.** The actions that are necessary in order to restore the system to a desirable state are described. They may be corrective actions in response to functional failures or potential failures.

• **Resource Needs.** Resources required for carrying out the corrective action are described. Examples are spare parts, consumables, labour, and equipment. Inspiration may be found in the definition of Maintenance Support Performance (a part of Availability Performance).

**Number 8: Foundation for Prioritisation**
The essence of FMEA is to identify and prevent known and potential problems of reaching the stakeholders. In order to achieve this some assumptions are made, for instance, about the priority of problems. Hence, finding appropriate priority for the problems is important and the thrust of the methodology. (Stamatis, 1995)

There are a number of different ways of prioritising the problems that should be solved. One traditional way is to calculate a Risk Priority Number (RPN). The RPN is the product of estimated values for occurrence (frequency), severity, and detection of the problem. However, one should be aware of the type of scale that is used to estimate the different factors. (Stamatis, 1995)

Rhee & Ishii (2003) state that the prioritising based on RPN is a product of three ordinal numbers, which not is appropriate to apply. Instead they suggest that the FMEA should be based on the products Life-Cycle Cost. The costs are based on judgement of variables such as frequency, detection time, fixing time, delay time, and parts cost.

The present author thinks that it is preferable to apply a Life-Cost Based approach to the FMEA, and not apply the traditional prioritising based on RPN.

• **Frequency of the Failure Mode.** The frequency of the failure mode is estimated. This work is often extensive and requires a detailed prediction of the frequency, which can only to a limited extent be based on relevant statistical data. Subjective estimations (of individuals or groups) are applied to a large extent. The methodologies that are applied should be possible to describe in order to give credibility to the analysis. One important quantity to clarify is the time-parameter, which may be, for instance, calendar time, operation time, or number of cycles. A multidimensional time concept may also be necessary.
• Conditional Probability of Stated Consequence or Scenario. At the estimation of the conditional probability of a stated consequence the existing management or control should be taken under consideration, for example FM/RM & BIT. The combination of 8a and 8b makes it possible to estimate the system safety implications, in the cases where stated consequences are related to system safety.

• Valuation of Stated Consequence. 8a, 8b and 8c1-3 give the opportunity to estimate the failure mode's influence on the system's life cycle cost.

• Immediate Loss. Loss of system, human life, property, or loss for third party.

• Corrective Cost. Immediate costs for performed measures and utilised resources.

• Cost for Loss of Function. Loss of income and compensation for loss of production.

• Times for Corrective Actions and Non-Availability. Together with 8a and 8b the influence on the system's availability performance can be estimated.

Supporting tools in this step may be classification of failures according to MIL-STD-882C and RCM.

Number 9: Decisions
It is appropriate to evaluate the performed FMEA. This evaluation can be made through three basic questions (Stamatis, 1995):

• Is the situation better than before?
• Is the situation worse than before?
• Is the situation the same as before?

The answer to the three questions listed above will be used to recommend actions and to see the result of those actions in the corresponding columns of the FMEA-sheet (Stamatis, 1995). The FMEA should primarily be a support for evaluating and prioritising actions for improvements. Decisions should be made on the basis of the qualitative data in 1-7 and the quantitative data in 8. The decision is primarily a choice between three alternatives:

• The system is acceptable and no improvements are necessary.
• There is some uncertainty and it is necessary to get better data and information, through testing or more detailed analyses and simulations.
• The situation is unacceptable and something, such as some improvements, has to be done at once.
If the situation is unacceptable typical recommendations may be (Stamatis, 1995):

- Add built-in detection devices. (Functional Monitoring, Built In Test)
- Provide alternatives to the system.
- Add a redundant subsystem. (Redundancy Management)

Other possible suggestions of appropriate actions may be found in MIL-STD-882C and RCM.

Three other pieces of information are also to be listed:

- The one who is Responsible for Measures.
- Concrete Proposal for Measures.
- Receipt of Performed Measure and Modified Analysis.

**FURTHER RESEARCH**

One possibility for further research is to study how the proposed framework can be implemented in an organisation. Here aspects such as the integration of proposed methodologies and tools with other methodologies and tools that have shared interfaces or functions are crucial. As one example, it seems as if the border between the technical system and the support system is becoming fuzzier due to an integration of traditional support documentation, such as fault localisation and other instructions, in the built-in system for Health Management. Another important aspect here is that of computerisation and software support of the work with stakeholder requirements and system functions, which seems natural since health data and information are intended to be collected once the technical system is in the operational phase. An implementation of something new also means that there are some organisational changes that must be considered. Once again core values such as Management Commitment and Everybody’s Participation are probably of great importance. In order to evaluate the practical contribution and value of the proposed framework and model a pilot study may be valuable. This pilot study would also contribute positively to the present study’s external validity.

**Design of Pilot Study**

Related to the implementation of the presented framework and model, some aspects of the proposed combination of methodologies and tools are applied in the framework of the research project in the form of a pilot study.
study; see Figures 7 and 8. The pilot study, which is divided into nine steps, is made in the form of a master’s thesis, and focuses on a subsystem in aircraft 39. The subsystem is for air-to-air refuelling, which is a function that has been added to the aircraft due to changed stakeholder requirements. The unit of analysis in the pilot study is stakeholder requirements and system functions. The pilot study may also be summarised by the proposed FMEA, see Table 5 or Figure 7.

<table>
<thead>
<tr>
<th>STEP</th>
<th>FOCUS</th>
<th>METHODOLOGY</th>
<th>FMEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3, 4, 5, 6, 9</td>
<td>Stakeholder system (Stakeholders &amp; Requirements)</td>
<td>Literature Study</td>
<td>0, 1</td>
</tr>
<tr>
<td>7, 8, 9</td>
<td>JOINT SYSTEM (Stakeholder Requirements &amp; System Functions)</td>
<td>Literature Study</td>
<td>2, 3, 4, 5, 6, 7</td>
</tr>
<tr>
<td>8, 9</td>
<td>FM/RM &amp; BIT (WHAT should be monitored and tested, i.e. what system functions, and WHY, i.e. according to what stakeholder requirements)</td>
<td>Literature study</td>
<td>8, 9</td>
</tr>
</tbody>
</table>

**Figure 7** Summary of the proposed pilot study for the purpose of evaluating aspects of the described framework and presented model. The figure summarises proposed steps, methodologies, and connection to the developed FMEA.

**Step 1: Identify and Structure the System**
Tool: tree diagram, affinity diagram
Methodology: literature study, cross functional team
Result: Chart 1 - System Structure

**Step 2: Identify and Structure Functions of the Aircraft**
Tool: tree diagram, affinity diagram
Methodology: literature study, cross functional team
Result: Chart 2 - Function Structure

**Step 3: Correlate System and Functions**
Tool: matrix diagram
Methodology: cross functional team
Result: Matrix 1 - System Function Matrix

**Step 4: Identify and Structure the System Stakeholders**
Tool: brainstorming, affinity diagram, tree diagram
Methodology: literature study, cross functional team
Result: Chart 3 - Stakeholder Structure

**Step 5: Identify and Structure Requirements of System Stakeholders**
Tool: brainstorming, affinity diagram, tree diagram
Methodology: literature study, cross functional team
Result: Chart 4 - Requirement Structure

**Step 6: Correlate Stakeholders and Requirements**
Tool: matrix diagram
Methodology: cross functional team
Result: Matrix 2 - Stakeholder requirements matrix

**Step 7: Correlate Requirements and System Functions**
Tool: matrix diagram
Methodology: cross functional team
Result: Matrix 3.1 Requirements on Systems Functions, Matrix 3.2 Requirements on Subsystem Functions, Matrix 3.3 Requirements on FM/RM & BIT

**Step 8: Give Recommendations on what should be Covered by FM/RM & BIT, and why**
Methodology: cross functional team, RCM, FMEA, FTA, SRA
Result: List 1 - What should be covered by FM/BIT and why, Matrix 4 - Correlation between functions and decision criteria

**Step 9: Evaluation of Each Step According to Evaluation Criteria (Strengths and Weaknesses)**
Result: List 2 - Comments about each step, (Matrix 5 - Correlations between step and evaluation criteria)
Figure 8 Summary of the proposed pilot study for the purpose to evaluate aspects of the described framework and presented model.
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