Incorporating Maintainability into the R&D Process

Based on a Case Study of a Ground Based Radar System

Master of Science Thesis [in the Master Degree Programme Product Development]

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Cover:
[Tools representing maintainability, for an explanation of what maintainability is at Saab EDS read chapter 4.2.]

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ABSTRACT

In this master thesis a method and suggested changes for how to improve the integration of maintainability in the product development process has been developed for a Swedish defence company by investigating a particular product. A change in the suppliers of the radar cabin for a ground based radar system increased the in-house mechanical design workload and did not sufficiently supported the maintainability of the delivered system. The system requirements were very function oriented and the maintainability requirements that should constrain the function requirements were kept at a general level. The Systems Design Department left the fulfilment of these constraints to the subsystems and it was only the system requirements for the entire system that was verified, not the individual units of the system.

The Mechanics and Environment Department does not have a systematic method for designing for maintainability and a unit is designed from the individual designer's experience. There are no guidelines that support good maintainability practices and less optimal design solutions have been discovered very late in the testing and verification phase which has caused late deliveries and large financial costs.

The improvement suggestions are based on a series of interviews and investigations of internal documents to identify the needs of the employees. A maintainability design specification has been created to increase the understanding and to gather relevant data in one worksheet. Other recommendations include improvements to the quality of the different reviews, an increase of the usage of visualisation tools and a better communication between the departments on what maintainability is and what values it is measured in.

Key words: Serviceability, maintainability, maintenance, service issues, maintainability requirements, maintainability worksheet, mean time to repair, mean time between failure, mean time between critical failure, MTTR, MTBF, MTBCF.

ACKNOWLEDGEMENTS

This master thesis was made upon the request from the Systems Design Department at Saab Electronic Defense Systems Operations Göteborg who defined a need for an investigation of how maintainability can be better integrated into the R&D-process. Though conducted at the Systems Design Department, the main focus was on how the Mechanics & Environment Department work. The thesis was conducted within the division of Product Development at Chalmers University of Technology.

We would like to start by expressing our appreciation to the employees at Saab Electronic Defense Systems Operations Göteborg who have taken their time to answer our questions and shared their knowledge. Without you this project would have been difficult to conduct. Special thanks go to our supervisor Jan Rydén, Senior Specialist, for your encouragement and guidance during the project.

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Göteborg, June 2013

Emma Andersson and Johan Ericson

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NOTATION

Components	
ACU	Air Conditioning Unit
ECU	Electronics Cooling Unit
LCU	Liquid Cooling Unit
PDU1	Power Distribution Unit 1
PDU2	Power Distribution Unit 2
SDU	Signal and Data Unit
TCU	Turntable Control Unit
TTU	TurnTable Unit
TRU	Transmitter Unit
Terms and Methods	
FMEA	Failure Mode and Effect Analysis
Maintainability analysis	Review of the maintainability by physically conducting the different maintenance operations and timing them to get the real value, not a prediction.
MTBF	Mean Time Before Failure
MTBCF	Mean Time Before Critical Failure
MTTR	Mean Time To Repair
Miscellaneous	
CAD	Computer Aided Design
EEH-report	EMW Exception Handling report
FMV	Försvarets materielverk, Swedish Defence Material Administration
LCB	Logistic Configuration Baseline document
ILS	Integrated Logistics Support (Department)
Reviews	
DR	Design Review (Doc. No. 1776)
HRW	Hardware Review (Doc. No. 177 65)
TRW	Technical Review (Doc. No. 177 63)
Products	
GAMB	Giraffe AMB – Giraffe Agile Multi-Beam
GAMB-1	The Giraffe AMB 1 (full name censured)
Giraffe AMB 1	The first upgraded Giraffe AMB - Product no.: UAZ10170/25
Giraffe AMB 2	The second upgraded Giraffe AMB - Product no.: UAZ10170/29
Arthur	A mobile Artillery Hunting Radar
Software	
IFS	Product Data Management (PDM) software to handle product data and documentation as well as functions for material data and manufacturers.
Pro/E	Pro/Engineer is a Computer Aided Design (CAD) tool used to create 3D-models and drawings.

1. INTRODUCTION

In a product with a long lifespan the maintainability of the products is very important, not only from a financial point of view but also to be able to maintain a high consistent performance level and high uptime throughout the products lifespan. In an industry with small order series that require adaption for the specific customer it is important to be able to reuse large parts of the previous design in a product. This introduction will give the reader a company background followed by a description of the product that has been the focus in this master thesis.

1.1.Background

Saab was founded in 1937 to secure Sweden's supply of military aircraft, and even though many other products have been introduced into the product portfolio since then, this has remained a core business for Saab (saabgroup.com, 2010). Today Saab is a global company with around 13.000 employees. Annual sales reach roughly SEK 24 billion, of which research and development account for about 20 percent. Acquisition and integration of other companies into the Saab family has helped to strengthen and widening the company's product portfolio and today Saab serves not only Sweden (see Figure 1-1), but the global market with products, services and solutions ranging from military defence to civil security. To manage the diversity in the product portfolio Saab is divided into six major business areas: Aeronautics, Dynamics, Electronic Defence Systems, Security and Defence Solutions, Support and Services and the independent subsidiary Combitech.

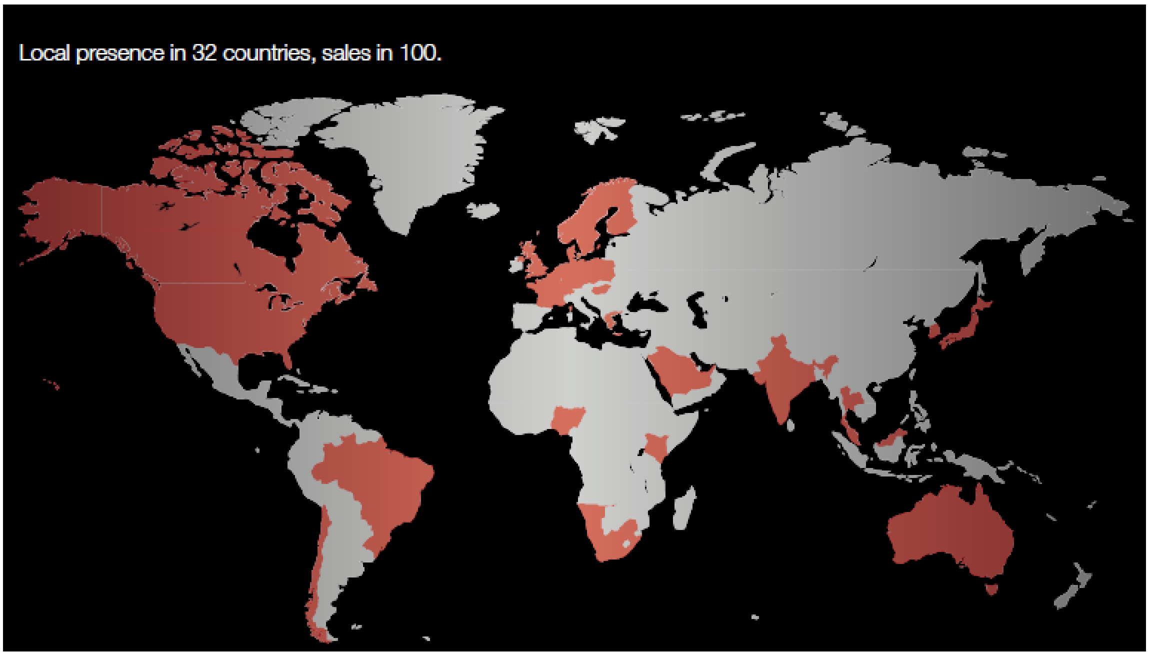


Figure 1-1 - Saab's presence and sales globally (saabgroup.com, 2010)

The organisational structure that Saab EDS Operations Gothenburg (EDS) currently employs is that of a traditional line structure (Rubenowitz, 2004) see Figure 1-2 for a visual image of the structure. The investigation was performed for Systems Design with a focus on Mechanics & Environment. Each function has technical authority within their specific area of expertise but is dependent on customer projects to receive resources. The amount of resources the functions are provided with by the projects depends on the activities needed from them in the different projects. A risk with having the functions so depended on the projects for funding is that the perspective of development can become very short. This result in non-standard solutions specific for each project, which may also led to degraded maintainability and inconsistencies in the design.

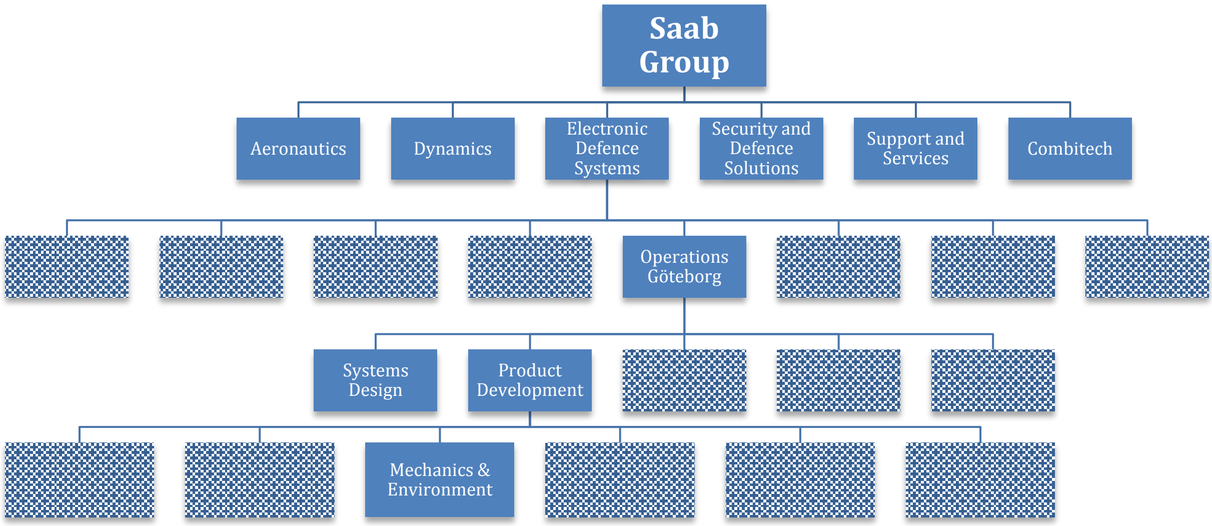


Figure 1-2 - Organisation overview

In the late 1970's the company began the development of a radar system called Saab Giraffe. Since its introduction there have been a series of upgrades of the system which is now at its third generation and it is this generation that is in focus for this thesis (see Figure 1-3). The Giraffe AMB is a surveillance system for use in both combat and peacekeeping situations. It has 360° coverage of the air volume around for air targets and is capable of simultaneously locating and warning against incoming Rocket, Artillery and Mortar (RAM) projectiles. The system is flexible and can be customised to integrate and operate with medium and short-range surface-to-air missile systems. Giraffe AMB also features an integrated command, control and communication system enabling it to operate as a command & control centre for both air defence and military air traffic control.

The Giraffe AMB exists in two main versions and the focus for this thesis has been the truck-mounted version in which the system is housed in a single 20 ft. ISO container. Available versions are:

- Giraffe AMB (truck-mounted system)
- Sea Giraffe AMB (ship-mounted system)

The major strengths of the Giraffe AMB system is its ability to carry out simultaneous multi-mission operations, its ability to detect, track, and classify many different targets regardless of the conditions and its high survivability with quick deployment time and high uptime. All this together with the fact that the system is fully self-contained, which ensures high mobility, makes the Giraffe AMB an important asset in all situations.

To ensure that the Giraffe AMB system remains a high performance product compared to rivalling products continuous improvements and development is important. An important aspect is the maintainability of the system, which affects how easy it is to maintain the system in a working condition. Factors influencing the maintainability is how often parts need to be checked, replaced, or repaired, how easy it is to perform the required operation and also how easy it is to locate an error if it occurs. The cost of maintaining the Giraffe AMB system stands for a big part of the total life cycle cost for the product and therefore it is desirable also from a cost perspective to increase the maintainability of the system. To ensure that maintainability aspects are better incorporated in future product development projects this thesis will, using the development of the Giraffe AMB (Agile Multi-Beam) as a base, investigate possible improvements to the development process. The method that will be used is that of a case study where previous development projects and components will be reviewed and studied from a maintainability point-of-view.

Figure 1-3 - Saab Giraffe AMB (saabgroup.com, 2010)

1.2.Purpose and Aims

For each company product there are a number of system requirements at a top level that are broken down into more detailed and specific requirements at a subsystem level. A central issue in this master thesis will be to investigate how these system requirements are practically implemented in the product development with a focus on maintainability. One point of interest is how the demands on maintainability from the top level are transformed when they make their way down in the organisation and how much is left to be interpreted by the design engineer. By illuminating a real case, the purpose is to contribute to increased knowledge of maintainability and how it is considered and realised in the development process. Actual improvement suggestions to the development process used at the company is also an expected outcome.

1.3.Research Questions

To aid as guiding points in the thesis work and for the readers of this report, a number of research questions have been created and developed throughout the investigation.

- RQ1: How are maintainability requirements created and developed in the product development process?
- RQ2: How are maintainability requirements and their fulfilment reviewed during the on-going development and verified in the finished system?
- RQ3: How can existing tools and methods integrate maintainability better and are there any new that could be implemented?

1.4.Delimitations

The physical units used as a base in this thesis are the ones located in the equipment room of the Giraffe AMB system, particularly the ECU (Electronics Cooling Unit) and its connecting air ducts. Even though there were other units that could have been interesting to investigate from a maintainability point-of-view, the focus in this thesis was on the actual development process, rather than the units themselves. Regarding the processes, the ones that have been studied are the ones used during the development of the new cabin for the Giraffe AMB, thus processes used during current on-going development projects of other systems at Saab has not been taken into consideration.

1.5.Outline

Chapter 1 presents an introduction to the thesis. It includes a background of the company and the product studied along with the research questions used, delimitations made and a general description of the report structure.

Chapter 2 provides a frame of references. First the definitions of terms and measures used in the thesis are presented, followed by the method FMEA and finally theory on requirements creation and their verification and validation.

Chapter 3 describes the research strategy used in the thesis, including the three stages evidence, interview and observation.

Chapter 4 presents the empirical data collected during the research. The data originates from internal company documents, interviews with employees and observations made at the company.

Chapter 5 contains the analysis and results based on chapter two and four.

Chapter 6 discusses the results made and the method that was used to obtain them.

Chapter 7 concludes the results of the research questions, the contributions of the thesis and possible future research areas.

Chapter 8 lists the thesis authors' recommendations to the company.

2. THEORETICAL BACKGROUND

In this section of the report the theory used to analyse the findings is presented. First the definition of terms and measures used in the thesis are covered, followed by the method FMEA and finally theory on requirements creation and their verification and validation.

2.1. Maintainability, Reliability and Serviceability

Highly relevant to the master thesis are the topics of maintainability, reliability and serviceability. These are sometimes used incorrectly when describing an activity and are sometimes mixed together. Therefore, a company jargon is important to establish to avoid misunderstandings and communication failure. Smith (2006) states that in complex mechanical and electrical analysis uncertainty of definitions can have negative consequences on how a requirement is fulfilled. Furthermore, a buyer's expectation of system is its reliability; how well it performs its function (Blischke & Murthy, 2003). Closely related to reliability is maintainability and serviceability which in turn can be measured in a number of other terms, listed in Table 2-1 and Table 2-2. To properly define what maintainability is the following definitions have been collected and are presented below.

Maintainability Definitions
"The probability that a failed item will be restored to operational effectiveness within a given period of time when the repair action is performed in accordance with prescribed procedures. This, in turn, can be paraphrased as 'the probability of repair in a given time' and is often expressed as a 'percentile down time'." (Smith, 2005)
"The "ability" of an item to be maintained, whereas maintenance constitutes a series of actions necessary to restore or retain an item in an effective operational state. Maintainability is a design parameter. Maintenance is required as a consequence of design". (Blanchard, et al., 1995)
"The probability that a failed item will be restored to its satisfactory operational state". (Dhillon, 2006)
"The ability of an item to be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair". (U.S. Department of Defense, 2005)

What the definitions of maintainability all have in common are that they speak of probability or ability to restore an item to operational state. The term serviceability, which is widely used at the Saab EDS, is not as easy to define. Few authors speak of an actual definition and it is not discussed much in literature. The only clear definition found is:

Serviceability Definition
"The degree of ease or difficulty with which an item can be restored to its working condition" (Dhillon, 2006)

Designing a good maintainable system is crucial for customer satisfaction and should be characterised by having to require as little time as possible for as low cost as possible and with as low use of resources as possible. Blanchard et al. (1995) also suggests that each design team should have a maintainability specialist as part of the team to aid the balance between maintainability and the many factors that affect the design. They also suggest several different tools and aids the team can make use of; examples of these are mentioned further ahead and are also showed in Figure 2-3.

Evidently, there are many terms and definitions used in the engineering industry. Even a specific term can have different interpretations and meaning which puts high demands on an organisation to clarify and implement its particular jargon. Therefore, the following terms in Table 2-1 are an excerpt of relevant definitions that will be used in this master thesis to remove any ambiguity on what is being referred to. How maintainability is actually measured is usually in several combined factors, a selection of these can be seen in Table 2-2.

Table 2-1 Further terms and definitions (Dhillon, 2006)

Maintenance	*All actions necessary* for retaining an item or equipment in, or restoring it to, a specified condition.
Reliability	The probability that an item will *perform its assigned mission* satisfactorily for the stated time period when used according to the specified conditions.
Availability	The probability that an item is *available for use* when required.
Mission time	The time during which the item is carrying out its assigned mission.
Downtime	The total time during which the item is not in satisfactory operating state.
Corrective Maintenance	The repair or unscheduled maintenance to return items, equipment or a specified state, performed because maintenance personnel or others perceived deficiencies or failures.

Table 2-2 Common maintainability measures (Blanchard, et al., 1995)

MTBM	*Mean time between maintenance* which considers scheduled and unscheduled maintenance requirements. **MTBF**[1] *mean time between failure* is included in this calculation and is a measure of reliability.
MTBCF1	*Mean time between critical failure* is not mentioned by Blanchard, et al. (1995) but is added to the list for its relevance. The term measures the same thing as MTBF but only considers the critical failures instead of all failures. For more information see chapter 2.1.2.
MTBR	*Mean time between replacements* is the time calculated to replace a part.
MDT	*Maintenance down time* is the total time the system is not performing its intended function. Included in the MDT is the mean active maintenance time which also includes **MTTR**1 *mean time to repair.*
TAT	*Turnaround time* is the time it takes for service, repair and check out an item for recommitment.
MLH/OH	Maintenance labour hours per system operating hour.
Cost/OH	*Maintenance cost* per *system operating hour* The maintenance cost should be considered in the context of *life cycle cost* (LCC).

To incorporate maintainability in the design Blanchard (1995) suggests the use of reliable and available standard components, enabling condition monitoring and good diagnostics for unscheduled maintenance. The latter can include accessibility for fast removal and replacement of broken components as well as labelling for rapid identification. Also, solutions for transportability and ease of handling as well as quick-release fasteners are mentioned as factors to consider.

For the customer, cost can be considerably lower for maintaining the system if the repair time is low and supporting resources are kept at a minimum. Therefore, by incorporating maintainability early in the design phase, the overall life cycle cost is reduced, which in turn increases customer satisfaction and the company profitability. A system can in general terms be described as in Figure 2-1 where the top row is related to consumer need fulfilment. However, the second and third row must be considered concurrently and early in the initial phases in order to get the necessary integration and priority.

[1] MTBF, MTBCF and MTTR are the maintainability measurements most frequently used in this case study as

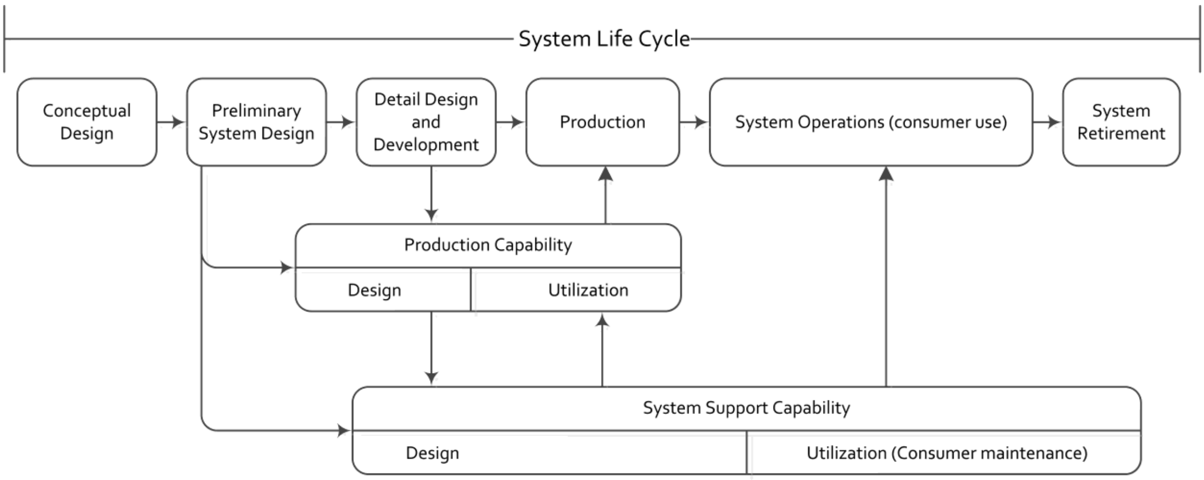


Figure 2-1 System life cycle (Blanchard, 1991, p. 4)

Traditionally, the sequential approach to system design considers only the major activities and in their respective order. This often leaves production and maintainability to be solved at the very end of the product development phase where the design is "fixed" and changes are expensive to make downstream, more on this in chapter 2.2 and Figure 2-5. In recent decades, new technology has caused modern systems to become increasingly complex. However, while the focus on these complex systems has been on performance, the effectiveness has decreased by neglecting the design parameters maintainability, reliability and quality which has also contributed to cost going up. Blanchard (1991) refers to the "iceberg effect", illustrated in Figure 2-2, of system life cycle and the difficulty with finding the long-term costs related to operation and maintenance. These costs have been found through "cause-and-effect relationships" and can be traced back to the decisions made in the early planning and concept phases. Furthermore, at the end of the preliminary design 60-70% of the projected life cycle cost is set for some systems. Therefore, it is vital that the top level of the system requirements contains the maintainability requirements and that the management and system engineering plan for the implementation. Maintainability should be integrated in the conceptual design phase and should be directly related to the expected functions of the system. The basic requirements on a top level should then be allocated down to the subsystem levels and ensure that the top level requirements will be met when all the subsystems' maintainability requirements are fulfilled.

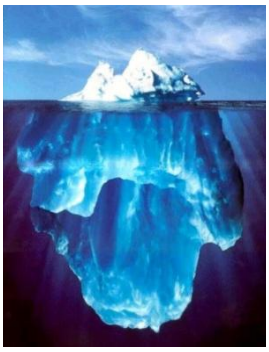


Figure 2-2 An illustration of the iceberg effect

It is advised that for every consumer need that is identified, it should be analysed with the process model seen in Figure 2-3 (Blanchard, et al., 1995). This method should ensure that maintainability of the need is met and addressed in all life cycle phases, see above Figure 2-1 of the system life cycle. Of course, each organisation needs to find its own level of detail and balance to the trade-offs necessary to realise the customer needs. It is recommended that for systems already in use iterative evaluations using a life cycle cost analysis could help to identify the high-cost contributors. In these instances, the use of maintainability tools like analysis and prediction models can significantly reduce the life cycle costs.

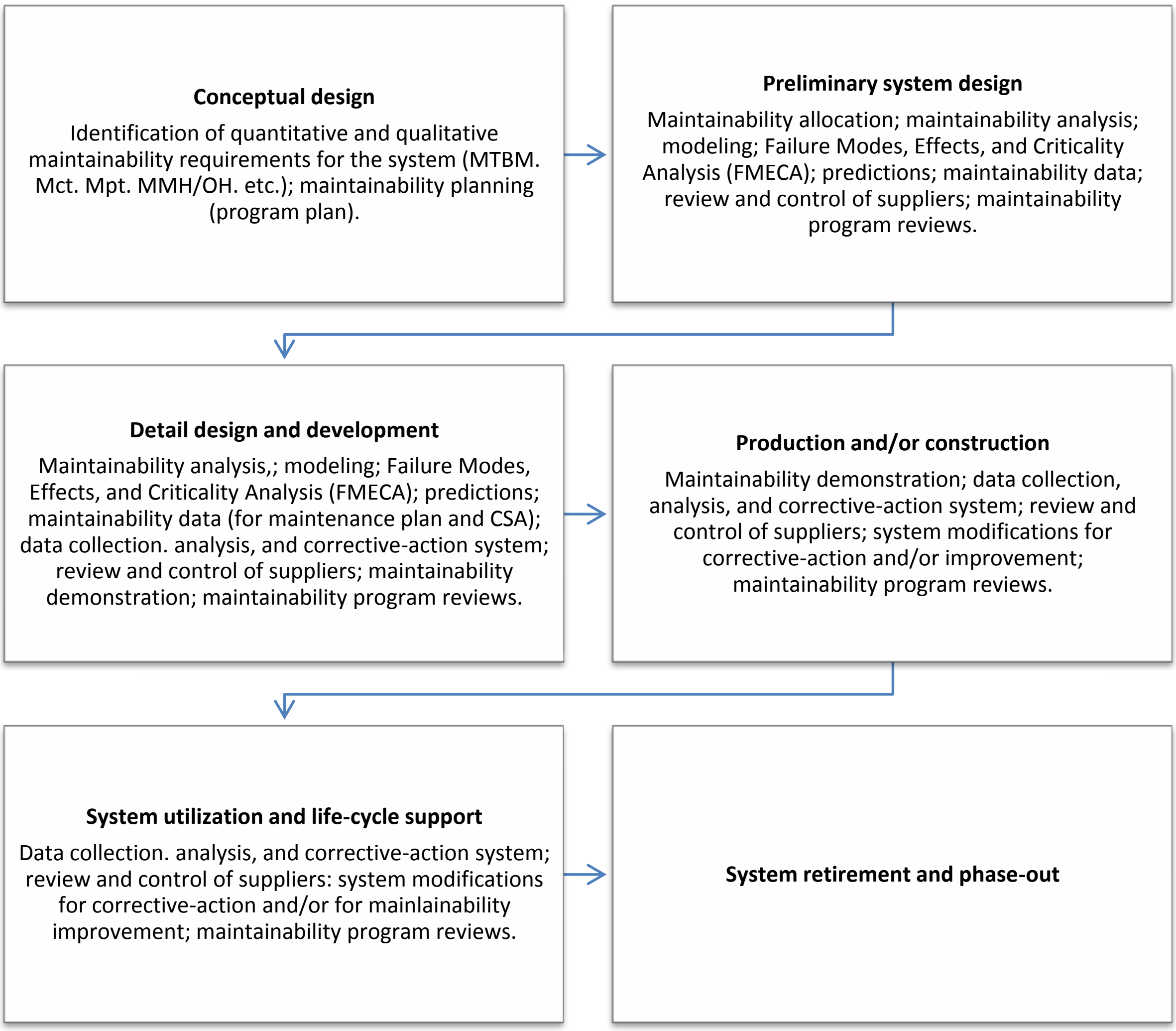


Figure 2-3 Maintainability in the system life cycle (Blanchard, et al., 1995, p. 99)

2.1.1. Down Time and Repair Time

The theory on down time and repair time presented in this chapter is central to the master thesis and has been integrated in the worksheet called *maintainability design specification* the authors have created. The worksheet is presented in chapter 5.6 and is also shown in appendices D, E and F.

To fully understand the maintainability process of a unit or component this chapter will cover the differences between mean down time (MDT) and mean time to repair (MTTR). Both are crucial to maximize the reliability and uptime of a system. As can be seen in Figure 2-4 the MDT and the MTTR overlap in some activities but should not be confused with being the same thing (Smith, 2011).

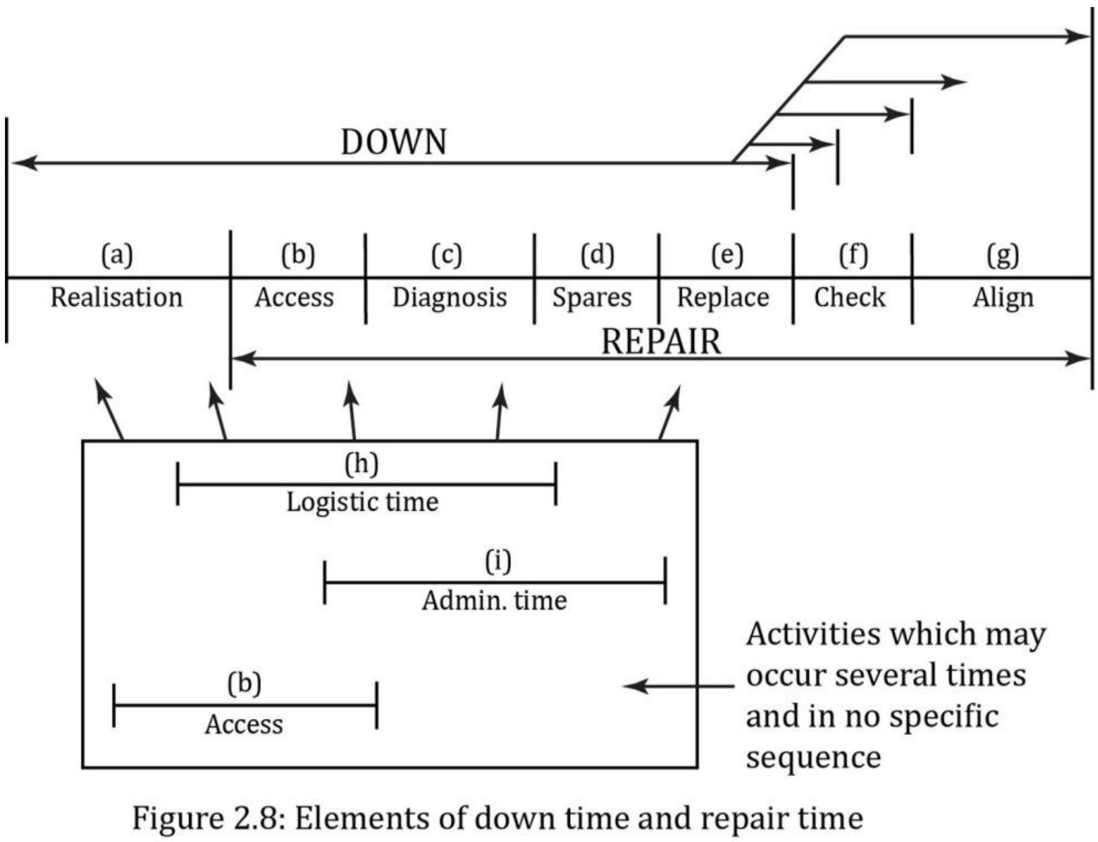


Figure 2-4 The different elements of down time and repair time (Smith, 2011, p. 23)

The different activities are described in detail below in Table 2-3. Activities b) - g) are so called *active repair* elements while h) - i) are *passive repair elements*. The active repair elements are mainly determined by mechanical design, environment, instructions, maintenance arrangements, manpower, tools and test equipment. Logistic and administrative time is mainly determined by the maintenance environment; the location of spares, manpower, equipment and the procedure for allocating tasks.

Table 2-3 Explanation of the activities in Figure 2-4

a)	**Realisation time**	This is the time that elapses before the fault (presumably dormant) becomes apparent (perhaps as a result of a regular proof test). This element contributes to unavailability but does not constitute part of the repair time.	
b)	**Access time**	This involves the time, from realisation that a fault exists, to make contact with displays and test points and so commence fault finding. This does not include travel but the removal of covers and shields and the connection of test equipment. This is determined largely by mechanical design.	Active repair elements
c)	**Diagnosis time**	This is referred to as fault finding and includes adjustment of test equipment (e.g. setting up a laptop or a generator), carrying out checks (e.g. examining waveforms for comparison with a handbook), interpretation of information gained (this may be aided by algorithms), verifying the conclusions drawn and deciding upon the corrective action.	
d)	**Spare part procurement**	Part procurement can be from the 'tool box', by cannibalisation or by taking a redundant identical assembly from some other part of the system. The time taken to move parts from a depot or store to the system is not included, being part of the logistic time.	
e)	**Replacement time**	This involves removal of the faulty LRA (Least Replaceable Assembly) followed by connection and wiring, as appropriate, of a replacement. The LRA is the replaceable item beyond which fault diagnosis does not continue. Replacement time is largely dependent on the choice of LRA and on mechanical design features such as the choice of connectors.	
f)	**Checkout time**	This involves verifying that the fault condition no longer exists and that the system is operational. It may be possible to restore the system to operation before completing the checkout, in which case, although a repair activity, it does not all constitute down time.	
g)	**Alignment time**	As a result of inserting a new module into the system, adjustments may be required. As in the case of checkout, some or all of the alignment may fall outside the down time.	
h)	**Logistic time**	This is the time consumed waiting for spares, test gear, additional tools and manpower to be transported to the system.	
i)	**Administrative time**	This is a function of the system user's organisation. Typical activities involve failure reporting (where this affects down time), allocation of repair tasks, manpower changeover due to demarcation arrangements, official breaks, disputes, etc.	

2.1.2. Failrate and its Usage

Failrate is the frequency with which a system or component fails, often expressed in failures per hour (or per million hours). If the failrate can be assumed to be constant (not varying over the life cycle of the system) it is useful to use the Mean Time Between Failures (MTBF) instead. It is defined as the inverse of the failrate (Smith, 2005).

In addition to MTBF there is also Mean Time Between Critical Failure (MTBCF). The difference between the two is that MTBCF only considers failures that are *critical.* For example a complex system can have many support functions that may be useful for the operation of the system, but not necessary. If a failure occurs in a component that does not affect the actual operational performance, it is not considered critical. An example of this in regards to this case study would be the Giraffe AMB. If a failure occurs that does not affect the actual uptime and precision of the radar system, e.g. it can still locate incoming objects at a certain height[2]; it is not a critical failure. As a result the MTBCF number is often significantly higher than the MTBF and can never be lower than MTBF.

The use of this failrate definition when designing maintenance and repair schedules gives an important advantage. Namely, that not every little failure needs to be regarded as something that requires attention right away. This is especially useful for products that are used in cases where the need for spare parts is a large cost or in other ways affect the user negatively (Example in a vehicle: taking up storage space that can be used for fuel instead) (James, 2006).

2.1.3. FMEA

FMEA stands for Failure Mode and Effect Analysis and is a method of systematically identifying and preventing product and process problems before they occur (McDermott, et al., 2009).The main focus of a FMEA is to prevent defects, increase safety, and gain customer satisfaction. The ideal way of working with FMEAs is to conduct them during the product design or process development stages, however conducting FMEAs on already existing products and processes can also be useful. If FMEAs are used early in the design and manufacturing processes, they have the possibility of substantially reducing the cost of developing a new product by identifying improvements early in the process when the cost of change is still relatively low. The end result will be a product that has been cheaper to develop, but at the same time is more robust since the need of after-the-fact corrective actions and late changes has been significantly reduced or even eliminated.

The FMEA Team

Generally one person is in charge of coordinating the FMEA process, however all FMEAs are team based (McDermott, et al., 2009). The main objective of a FMEA team is to contribute with a mix of perspectives and experiences to the project and because of this it is inappropriate to have a permanent FMEA team. Instead it should be adapted and the composition of the team should be dictated by the specific task or objective at hand. That said, it is not necessary to replace all the team

[2] Defining what function the radar needs to fulfil to be considered non-critical varies with the customer requirements. For some it might be acceptable to only be able to locate objects within a certain height where the threat is perceived as most likely etc.

members each time, but replacing a few of them is an easy way of assuring a fresh perspective of problems and solutions.

Suitable sizes for FMEA teams are often between four to six people with the minimum dictated by the number of different areas affected by the FMEA. The different affected areas (engineering, manufacturing, service etc.) should all be represented in the team and if suitable, the customer of the product being developed may also be included to contribute with another unique perspective.

FMEA Integrated into the Company Quality Processes

While FMEA methods can be used as standalone methods, the full benefit of them comes when they are part of a comprehensive quality process that support the FMEA by giving high quality inputs and then being able to respond to the outputs of the method. For example, effective use of data and information is a key in a comprehensive quality process and without accurate product or process data the FMEA gets based on opinions rather than facts and loses its focus. This may result in critical failures going unnoticed in the product or missing out on opportunities for improvement.

2.2. Front Loading the Development Process

In the beginning of a product development project where a completely new product is to be developed, the designers start off with a blank page (Blanchard & Fabrycky, 2006). During the project more and more requirements are added which influences the ability to change the design. As actual designing of the product commences the ability to make big changes to the design gets smaller and smaller and costs more and more money, which can be seen in Figure 2-5. By "front-loading" the development, a greater work effort is put in the beginning of the project when the influence over the design is bigger. In the real world development projects rarely starts off with a blank page, but that does not affect the fact the possibility to change is dramatically reduced as development progresses. Maintainability is just one of the many aspects that will benefit from gathering as much information as possible in the early phases to avoid late and costly changes. In the case of the Giraffe AMB 1 and the reason for mentioning the importance of front loading is that the Giraffe AMB 1 was delayed and some of the contributing factors were late changes and faults discovered late in the development process.

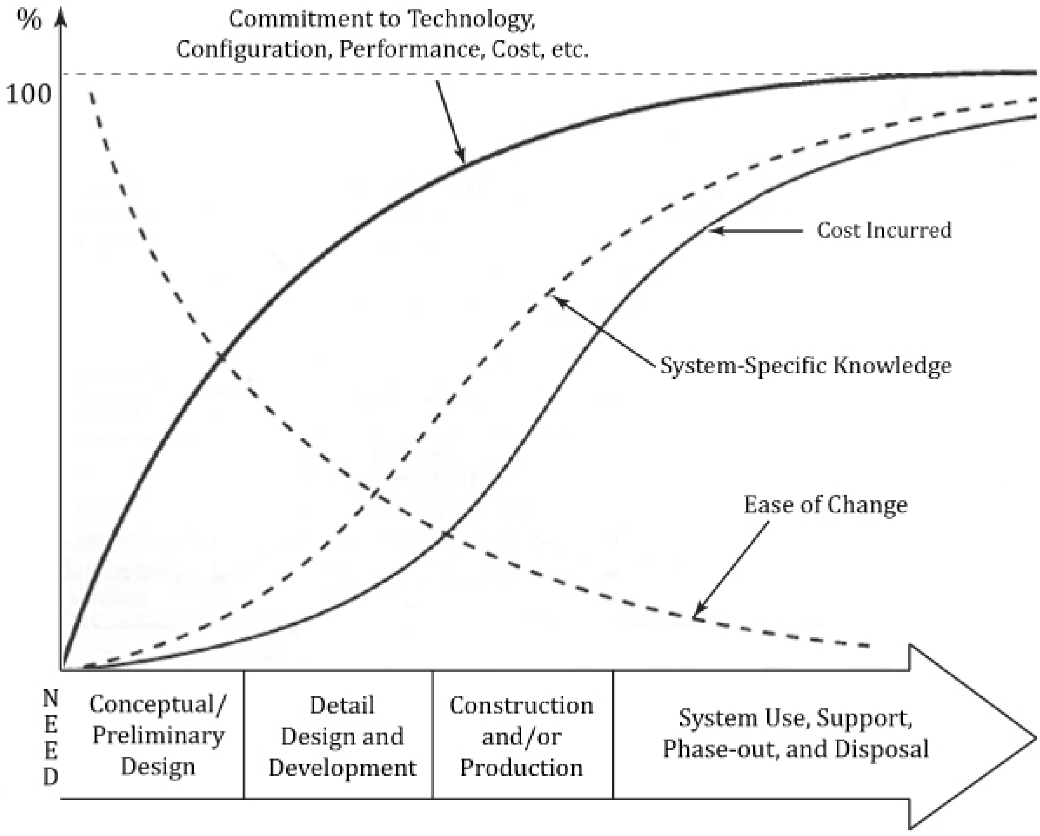
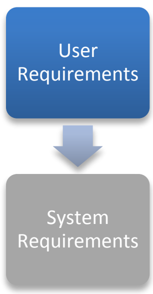


Figure 2-5 Ease of change vs. cost (Blanchard & Fabrycky, 2006)

2.3.Requirements

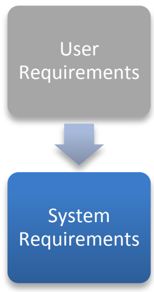
There are two types of requirements that should be mentioned for their different purposes: the user requirements and the system requirements. These two types of requirements are mentioned to give the reader a more comprehensive picture of the topic. Though for this master thesis the focus will be put on the system requirements and their fulfilment at a subsystem level. A case study regarding another industry's management of requirements is also included in this chapter to provide a more practical and less theoretical point of view. Lastly, a short introduction to verification and validation is given as it is a necessary element of any requirement; the ability to verify that the requirement has been met.

2.3.1. User Requirements

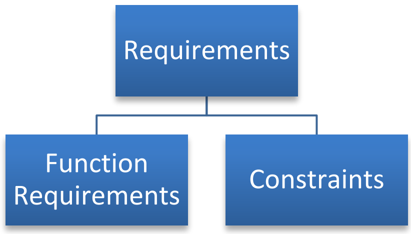


The user requirements describe what the system will deliver to the users and the system requirements describe the actual system (Stevens, et al., 1998). Mixing these two types together is not recommended because it removes the ability to check them against each other. The authors' continue by stating that user requirements should be able to be fulfilled through the system requirements and they should also be short and non-technical. Since this master thesis only investigates the developers' interpretation of requirements it will only cover the system requirements' aspects. It is further advised by Stevens et al. that all components on subsystem levels consider the needs of the user even though the users will not directly benefit from it. It is also recommended that the subsystem designers have the opportunity to communicate with the end users regarding their requirements.

2.3.2. System Requirements



The system requirements are established to describe what the system will do rather than how it will be done (Stevens, et al., 1998). The purpose of the system requirements is to function as a link between the user and the subsystem requirements and give the designers guidelines on how to fulfil the user requirements. They should also be formulated in such a way that they are understandable by almost everyone in a project which means that they should be short and clear. It is also recommended that they are non-technical without reducing their accuracy. Stevens et al. describe several methods on how to present requirements and their relationships in figures but also states that these should be accompanied by natural language with more precise definitions. A common mistake in creating system requirements is to put a single designer on the task of setting up a detailed description of the requirements in software tools which are then reviewed. This removes the creative element of an activity which should involve several system designers. Furthermore, system requirements should be broken down hierarchically and be decomposed two to three levels at a time.



Writing system requirements is generally a straight forward process. However, these can be divided into two groups; function requirements and constraints. This means that requirements on MTTR, MTBF and MTBCF are all constraining; they limit possible system solutions and are therefore called constraints. These do not add anything new to the product or system in terms of function but they are essential for the quality and customer satisfaction. However, constructing constraints without a cost-benefit analysis related to the user requirements can result in unnecessary and costly requirements.

There is no general methodology that meets a company's need to organise and define their system requirements. Instead, companies have to mix and match tools and methods that suit their own needs and their particular product. There are methodologies that do not consider constraints but these methodologies should not be applied in system design and they were often developed specifically for software design rather than physical products. There are a few general guidelines for creating a good system requirements document that should be noted (Stevens, et al., 1998):

- Question and remove unnecessary design decisions in requirements.
- Encapsulate and localise critical interfaces and real-time interfaces – critical can refer to a variety of safety-critical, complexity or cost aspects.
- Aim the breakdown toward existing commercial components or other elements that can be re-used.
- Keep the system requirements document small and understandable.
- Do not imagine that novel methods or software tools can solve your problems; they can succeed only if you have a good underlying process.
- Do not allow one engineer to create the whole set of requirements – use group brainstorming techniques.

2.3.3. Requirements Management from a Practical Case Study

Much of the theory used in this master thesis is based on academic studies to offer a broad and general view on systems engineering. However, for more practical references on an actual case in a specific business the following chapter on requirements management will give the reader a much more detailed account of relevant issues and recognise the similarities in problems related to requirements management. The findings of the case study of a Swedish car manufacturer have been summarised in the bullet points below and then discussed further in the unabridged version.

- There is no formal requirements specification in the early stages of a development project.
- There is a standardised design prerequisites document that captures all system requirements for components in the underlying sub-projects.
- The requirement documents lacked a summary of the most important requirements and a lot of documents were cross-referenced which caused a knowledge loss and confusion.
- The requirements did not communicate why they needed to be fulfilled which limited the design engineers' ability to interpret them.
- The requirements were interpreted differently depending on the verification method assigned to check their fulfilment.
- Reasons found for changes in the requirements during the product development process were said to be caused by knowledge gained during the process, conflicting requirements, technical difficulties, unanticipated function-sharing, demands on cost savings, new legal requirements and changes in the market.
- The company has a sign-off process where a requirement specialist and a system or subsystem task manager formally sign off on the requirements. However, it was only the management and not the project members who took part in the requirements fulfilment status.
- The requirements not championed by an individual or a requirement specialist did not receive enough attention and risked being unfulfilled.
- Communication and passion for product outcome was seen as factors for successful problem solving and end results.

Few empirical studies of how requirements management is practically carried out (Almefelt, et al., 2006). There are studies published on how to implement requirement management tools and reflections on how requirements in a project was manage and further on communication flows in teams. However, the authors aim in their study of a Swedish car manufacturing company to fill this void with a broad empirical view on requirements management.

Almefelt et al. (2006) describes the car manufacturer's development process as having evolved in recent years and that the requirements specifications have become much more rigorous. Follow-ups are stricter and the traceability of requirements has improved. The very early phases of a development project do not have a formal requirements specification but rather has a preliminary specification based on assumed overall prerequisites and technical knowledge. These are later used in the formal requirements break-down process and contribute with gained knowledge of e.g. advanced engineering.

Highly relevant to this master thesis's case study are the findings made on how each sub-project in the development is managing the system requirements, which is referred in the paper as engineering requirements. These sub-projects are all based on a standardised design prerequisites document which intends to capture all system requirements for the components or system that are included in the sub-project. The document is also the main document used when target agreements are made with external suppliers. The study also observes that the majority of the requirements are not formulated neutrally in relation to the final solutions. Instead, the car manufacturing company's final requirements are formulated when the solutions are already well known.

The interviewees voiced concerns regarding the lack of a clarifying system that explains interfaces and relationships between interdependent systems and their requirements. The study also found that there were a lot of referencing back and forth between documents and their requirements, resulting in limited access for some and confusion of the vast amount of documents and requirements that exist. The company employees expressed a wish for a summary of the most important requirements that must be fulfilled. Furthermore, informal requirements management like the use of e-mail, formal and informal meetings and databases are important to successfully communicate the requirements, no matter how well written they are. However, the requirements are not viewed as sufficiently well-formulated and many of the respondents at the car manufacturing company expressed a desire to understand the underlying intent of each requirement. The study also showed that design engineers interpreted requirements differently depending on what method of verification it was assigned to.

Reasons found for changes in the requirements during the product development process were said to be caused by knowledge gained during the process, conflicting requirements, technical difficulties, unanticipated function-sharing, demands on cost savings, new legal requirements and changes in the market. These changes can all be found in academic research on changing requirements and are all fairly standard causes for why requirements change. Practically in the company, requirements change as a result of discussions within a team and testing of preliminary requirements. Furthermore, as a method of handling requirements fulfilment the company has sign-off processes where a requirement specialist and a system or subsystem task manager formally sign off on the requirements. The requirement specialist is stated to have an important role in reporting on the requirements fulfilment status, the research study showed that it was only the management who received this information and not always the project members. Almefelt et al. states that this could be an important motivator for a team and how emphasis should be given to provide feedback to all involved.

The final recommendations the research group gives the car manufacturer are related to how the requirements are differentiated and presented. Those requirements not championed by an individual or a requirement specialist do not get enough attention and risks being suppressed and unfulfilled. Important cross-system requirements also need to be summarised and shared to avoid unnecessary late changes. Finally, emphasis on the informal requirements management is made and the importance of communication and passion for product outcome which can greatly affect problem solving and the end results.

2.4.Verification and Validation

In order to determine whether the system specifications are met or not the finished product is investigated by the verification and validation (V&V) discipline (Stevens, et al., 1998). The discipline also defines *how* the requirements will be verified and this is most often done during the conceptual design phase in the beginning of development (Blanchard & Fabrycky, 2006). Common ways of verification is inspections, tests or demonstrations. Without a method for verifying requirements they become meaningless since then there is no way of determining their degree of fulfilment.

Test methods and tools are provided by the V&V and the discipline is often responsible for the review management for the project manager (Stevens, et al., 1998). Traceability is highly relevant for the V&V since it is a method to trace actions and check these against the requirements; if and when the actions were performed and why. Finally, auditing is listed as a task performed by the V&V. Since systems engineering involves a lot of delegating there is a great need for trust and reliability that the work is being carried out properly. Auditing is a quality check to ensure that the work is being performed according to reality and not only what actions are being reported and documented.

A *technical review* is a review of the whole system. Another type of review is the *intermediate review* which is less formal and does not need to take as long. A considerable cost can be avoided by picking up problems early in the development phase rather than discovering changes later, see chapter 2.2 on front loading, cost and effects in the development. Two other types of reviews are walkthroughs and inspections where the first is designed to find problems before the requirements are fixed and the latter is a more formal and measured review of documentation. Both methods are beneficial for the quality of the work that will be reviewed. Also, it is stated that if others know their work will be inspected, the produced material will be better.

3. RESEARCH STRATEGY - CASE STUDY

There are a numerous number of methods to use when gathering empirical data. However, for a study of organisational processes a case study is particularly suitable to use (Cassell & Symon, 2004). The approach enables the researcher(s) to gather rich data on several groups operating within an organisation. It is stated that a case study is not a method but rather a research strategy that contains several methods such as qualitative and quantitative data collection. Breaking these methods down in further detail yields observations, interviews, questionnaires, focus groups etc. and are usually combined in some way to triangulate data in complex environments. See Figure 3-1 for a visual representation of the structure where the coloured methods are the ones utilised in this thesis. Furthermore, initially in the case study the researcher(s) should pay close attention to the "gatekeepers" of the organizational structure. These have the influence to introduce the researcher(s) to crucial informants and key players. Both internal and external stakeholders can be valuable to map out as soon as possible in the research as well as a sense of politics of the organisation.

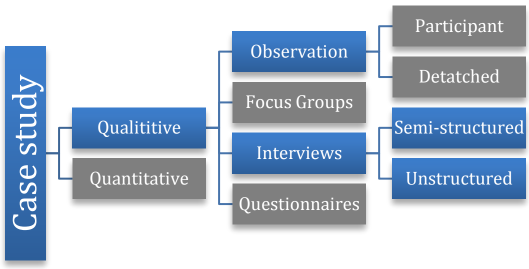


Figure 3-1 Hierarchy of the research strategy and methods

A case study research is not chosen to *sample* research and is not studied to understand *other cases* (Stake, 1995). The main task is to understand the intrinsic case study; the case that has been pre-selected. It is also worth noting that particularisation rather than generalisation is a crucial part to using the case study strategy for research. The researcher(s) should be objective gatherers of data but also need to be able to interpret what is happening and why. This can lead to a redefinition of the original research questions when more important underlying issues are made known.

In a case study, so called "evidence" is useful to the researcher(s) (Gillham, 2010). The quality and accuracy of the evidence can vary and it is suggested that it is sorted by type. Also, *different types* of evidence are recommended as well as using *multiple sources* to be able to construct a chain of evidence at the end of the case study. The evidence headings that are suggested for collecting large amount of data are as follows: Documents, records, interviews, detached observations, participant observation and physical artefacts.

Figure 3-2 Triangulation of the Research Questions

Therefore, the following three main methods have been chosen to support this case study research; Documents, observation and interviews to triangulate data as illustrated in Figure 3-2. Each of the three methods and how they are applied is explained in further detail below.

3.1. Documents

As previously stated, the evidence is divided into different categories to help organise the vast amount of data that is likely to be found (Gillham, 2010). The studied items of the evidence method further include:

- Documents – regulations, guidelines and policy statements.
- Records – Past documents that can offer insight on the present situation.
- Physical artefacts – The products that are produced, sketches, mock-ups, prototypes etc.

Practically, the gathering of these three items will mostly be done internally, e.g. how guidelines and templates are designed to support the development process from a maintainability perspective. The document method should provide the authors an indication of how the organisation is structured and what the goals are. Comparing documents, records and physical artefacts of a theoretical organisation with a practically mapped out organization will offer insight and possibly solutions to the difficulties that are experienced today.

3.2. Interview

Interviewing is a time consuming task and depending on the task and the number of interviewees different approaches should be taken (Gillham, 2010). The time cost is usually the main determining factor but also the character of the questions being asked, see Table 3-1 for a more detailed description of the different question types. Interviews are commonly used when there are few numbers of subjects to be interviewed who are accessible, the subjects are crucial to the outcome, the expected answers are extensive and requires probing and when the questions are sensitive and requires a certain level of trust to be built up to gain an honest answer.

Table 3-1 "The verbal data dimension" (Gillham, 2010)

Unstructured						**Structured**
Listening to other people's conversations; a kind of verbal observation	Using "natural" conversation to ask research questions	"Open-ended" interviews; just a few key open questions, e.g. "elite interviewing"	Semi-structured interviews, i.e. open and closed questions	Recording schedules: in effect, verbally administered questionnaires	Semi-structured questionnaires: multiple choice and open questions	Structured questionnaires: simple, specific, closed questions

All interviews conducted in this master thesis are based on semi-structured interviews. The choice for this particular method is to learn as much as possible of the practical implementation of the system requirements through the organization. This requires the interviewee to be allowed to speak freely and offer insight outside the questionnaire's structure. Closed questions are asked when the interviewers need confirmation of evidence found in the organization though these are expected to lead to further insight in why certain guidelines and processes are not functioning properly.

3.3. Observation

Observation is a method of data collection that is most direct of the three and yields the most accurate information in a case study (Gillham, 2010). It is not what has been written or what people say happens. However, for untrained observers the method can result in highly selective and biased information gathering. It is recommended that during observation the researcher consistently tries to understand the effects his or hers presence have on what takes place and whether or not it is characteristic on the situation. If not, the research information might not be valid.

Three main elements are listed as the very simplest form of observation:

- "Watching what people do;
- Listening to what they say;
- Sometimes asking them clarifying questions."

Further, Observation can be seen as either participant observation where the observer is directly involved, or detached/structured where the observer watch from the "outside". Though the methods are different, the first being qualitative and the latter quantitative, both can be used and mixed to gain as much information as possible. Literature also speaks of different degrees of each observation method where the researcher(s) should take care of the "getting-to-know" phase and initially keep a low profile.

Observations of both participant and detached nature will be performed throughout the master thesis period quite naturally which will indicate areas where the authors might find additional information. However, this can as theory suggests, cause selective information gathering and even result in scope creep. This will actively be considered throughout the thesis work and be avoided to the authors' best ability.

4. EMPIRICAL FINDINGS

In this chapter empirical findings made at the company will be presented. The findings are based on the interviews conducted as well as internal documents provided by the company's document system and intranet. The entire list of interviews conducted can be found in Appendix B and the question sheets in Appendix C. The product used to investigate the company's approach to maintainability was introduced in chapter 1; the Giraffe AMB.

4.1. Research Project - The Update of the Giraffe AMB Cabin

The development of the Giraffe AMB was triggered by a need to develop a new cabin as result of the loss of a large supplier that delivered the entire cabin. The update included a new shelter, a new liquid cooling system, new power supply and a new turntable. A decision was also made to be less dependent on one supplier delivering many components and Saab therefore contracted several suppliers delivering a few components each. One of the main aspects in this project that was said[3] to be considered was the maintainability but there was no particular method used to communicate this to the subsystem designers. The development project started as a research project but when the company received a customer order of the system during this research it was rushed with many new subsystem designers added to the project. This meant that the maintainability was neglected and because there had never been any guidelines at the top system level to begin with regarding this and the customer order meant that the project shifted focus. However, the new Giraffe AMB did become more modular and it was easier to change units than the previous model. Also worth noting, there is a trade-off between a unit's failrate and its mean time to repair; if a unit rarely breaks down, how much time should be spent on designing it for easy replacement? A Systems Engineer[3] stated that it is important to define failrate dependent MTTR requirements early in the development phase.

The Giraffe AMB is sold in very small series and each series is adapted after the customer's wishes and demands. This means that old and new units are mixed together, units that have had different designers and different methods to fulfil the requirements for each. 5-10% of the Giraffe AMB is remade in a new customer order and new development is very expensive. The product is sold with a life expectancy of 20 years[4] which makes the maintainability important for the product's reliability.

The Investigation

All references to the specific Giraffe AMB that has been investigated will be named Giraffe AMB 1 for confidentiality purposes. A Giraffe AMB that was developed later and is occasionally mentioned will be referenced as Giraffe AMB 2.

[3] Systems Engineer interviewed by: Ericson, J. & Andersson, E. (11th February 2013)
[4] Document number: 2/1029-UAZ10170/25

At the top of the system structure there is a document[5] that provides an overview of the documents drawn up for the development. However, this document was not seen referenced in any other sub-document during the authors' investigation and it was through an informal interview that it was discovered. Since it was part of a larger project it had a different product number than the Giraffe AMB investigated and the overview of the document structure was not discovered until late in the investigation. For someone from the outside of the company there does not appear to be a logical structure of the documents drawn up or their relation to each other unless you have the specific knowledge of how projects are connected. The document5 at the top of the system provides the inexperienced reader with a quick overview of the requirement specifications created for the Giraffe AMB. There are a total of eight documents describing the requirements baseline of the Giraffe AMB and two of these, listed in Table 4-1, contain relevant information of the maintainability requirements. These have been the main source of data during this master thesis and were found through database searches of the combination 1029 (the company code for requirement specifications) and the document number UAZ10170/25 (for the Giraffe AMB 1).

Table 4-1 The two requirement specification documents for the Giraffe AMB describing maintainability aspects

Doc. No.	Document Title
1029-UAZ10170/25	Requirement Specification for GAMB-1[6]
2/1029-UAZ10170/25	Requirement Specification for Enclosure in GIRAFFE AMB

In the document *Requirement Specification for GAMB-1*[6] there is a headline for "non-functional requirements", which is what the authors refer to as *constraints* in this thesis, see chapter 2.3.2 for theory on the terminology. All points covered regarding non-functional requirements, e.g. maintainability, references to the document *Requirement Specification for Enclosure in GIRAFFE AMB.* The relevant prerequisites from the document that concerns this thesis can be found in Appendix A. This document only contains general requirements for the system as a whole and states that it shall form a base for further detailed specifications of the subsystems. Looking at maintainability, there are no requirements set on a lower level than for the entire enclosure. From there on only design specifications are set as can be seen in Table 4-2, the units in a system are not provided with any maintainability requirements. The different documents and their content will be further mentioned and visualised in chapter 4.8 in a summary of the investigation where the maintainability values have been added in.

Table 4-2 The design specifications for the enclosure and the climatic system

Doc. No.	Document Title
10/10262-UAZ10170/25	Konstruktionsspec för AMB 1 ENCLOSURE
14/10262-UAZ10170/25	Design Specification for the Giraffe AMB Climatic System

[5] Document number: 1090-2/FCP1041264
[6] The real name has been replaced with a 1 for confidentiality purposes

4.2. Maintainability at Saab EDS

Maintainability at the company has a wide definition and includes more than just the ability to perform routine service tasks on the product. Incorporated into maintainability is also the ability to maintain the product in a working condition, which may involve performing various repairs of different complexity on the product. These repair tasks can range from simple tasks where small, easy accessible components are replaced, to much more complex operations involving the replacement of entire units requiring a significant work effort. The terms used by the company to measure maintainability is Mean Time To Repair (MTTR), Mean Time To Failure (MTBF) and Mean Time To Critical Failure (MTBCF), also described in the theory chapter 2.1. The company sometimes uses the term *serviceability* instead of *maintainability* when referring to what the thesis authors have, with support from theory, chosen to call *maintainability*.

One of the reasons that the products have a relatively low degree of maintainability today is explained by several of the interviewees.[7] They believe that the many consultants involved in a project often lacked the proper understanding for the company products. Since they were put on a very specific task, e.g. a small detail in a subsystem, they were not provided with sufficient guidelines or work method descriptions. Maintainability is one of the areas that suffer from bringing in external people. During the meeting it was further stated that “Saab is very function-oriented. You pack in as many systems with different functions as possible but seldom leave any space to be able to service the product. The designer has no comprehension of what is visible and available. They are put on a small part, e.g. a box, and have almost no understanding of what happens outside it.” Also, “The maintainability suffers too much for how the design work is performed. You trust the 3D-CAD too much, though it has been a bit better since we started working with mock-ups.”

There is a workshop held by the company’s marketing department each year with its customers to get feed-back. But the knowledge that is gained at these rarely gets backs to the system designers. According to a subsystem designer[8] they never receive any feedback unless something has gone really bad. This result in a process where the same type of errors can be done over and over again without being brought to the attention of the responsible engineer.

From an interview[9] regarding iterations and poor maintainability the following was mentioned. At one occasion a subsystem design had resulted in major maintainability issues and a representative from the ILS Department decided to bring the subsystem designers out to the physical system that had been assembled in the assembly halls to discuss the maintainability problems. However, a meeting like this is only done when a serious issue has occurred that makes validation and customer delivery impossible. It was also done very late in the development process since this is at a stage where the system has already been physically assembled, a phase which can cause high costs and time delays.

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[7] Two System Engineers, an ILS Manager, a Systems Verification Engineer interviewed by: Ericson, J. & Andersson, E. (24th January 2013)

[8] Subsystem Designer interviewed by: Ericson, J. & Andersson, E. (11th February 2013)

[9] ILS Manager interviewed by: Ericson, J. & Andersson, E. (30th January 2013)

Maintainability and ILS

The maintainability aspects at the company are mainly upheld by the ILS, Integrated Logistic Support Department. They work with maintenance analyses and educate customers in how to use and maintain the systems they buy. They are included in the steering group that manage the system development process and continually review the project progress at stage gates. In the case of the Giraffe AMB's development ILS joined the development process when the procurement of power plants and the selection of suppliers took place.

ILS is supposed to provide input on the product design from a maintainability perspective at the review meetings. This was difficult to do in the Giraffe AMB project[9] because they received their data late and the reviews were based on the subsystem designers' solutions from a computer generated 3D-model. Very little was done with physical prototypes and the design results were not visualised other than with the 3D-model until the actual system assembly was done.

Supporting Documents and Guidelines

From one of the interviews[10] conducted an example of how knowledge on maintainability has been lost over time was given. There used to be a document describing recommended distances for different units' required opening mechanisms, e.g. the distance a unit's door requires to be able to be opened. The document was used before the company moved to computer aided design, CAD, and has since been forgotten. Today the practice of ensuring proper distances is done by simply creating an extra surface in the computer model and by experience judge if the distance is acceptable or not. A few designers use the integrated function with manikins to visualise human usage but it is not a demand and does not appear to be very well known or practiced.

Subsystem designers receive little information of how to interpret the requirements that are provided on maintainability. The requirements and maintainability prerequisites are presented in values and numbers that are difficult to transform into actual design guidelines and the designers usually design from personal judgement on how a solution should be realised. Two of the interviewees[10,11] think that the requirements on maintainability should be made more specific and offer better guidelines and support. It is also stated that the projects are rushed too fast into the detail level which means that important decisions are made on a detail level, decisions that should be made on a much higher system level where the understanding for the entire system solution is greater.

4.3.Organisation and Departments Overview

The company's product development process is described in the sequence shown below in Figure 4-1. The scope of this master thesis limits the investigation to the blocks "Define System Requirements" to "Get System Acceptance".

[10] Design Engineer interviewed by: Ericson, J. & Andersson, E. (11th February 2013)
[11] ILS Manager interviewed by: Ericson, J. & Andersson, E. (29th January 2013)

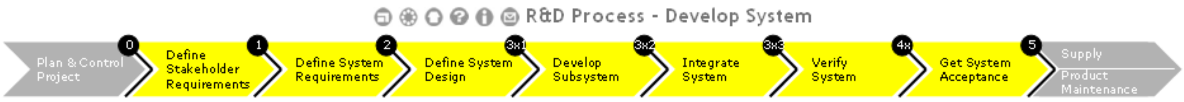

Figure 4-1 The R&D process at the company

A comment on the process used in the development work and how it through this structure can indirectly affect the maintainability is briefly covered in this subchapter. The design of the process does not offer a logical overview, at least not for the sublevels. For each sublevel it changes without connection to the previous higher level and reorganises parts of the structure. Several clicks and steps are required for an inexperienced user and it does not encourage a system or process mind-set. From interviews with system and design engineers it became evident that the manuals, guidelines, templates and examples that can be found at each of the process blocks are not used very extensively and the users rather use an old document they have previously used and adapt it to the new case.

The Mechanics and Environment Department has their own collection of documents outside the R&D process ("A-Ö list, extended support documents") with a more rigorous and comprehensive list to work from. The designers are more comfortable in using this list than the information available in the R&D process. It does not contain actual links to files like the R&D-process but rather the document number which can then be used to search the document management software IFS. This ensures that the designer always knows that that they are working in the latest version of the template and that they are using the correct work method since these are listed according to revision and date. The list can be accessed from the 3D-modelling program Pro/Engineer, from the R&D process and many designers also have the webpage as a shortcut in their browser. This is considered to be more convenient than clicking through the many steps in the R&D process where there is an uncertainty of exactly where the Mechanics and Environment Department is located in the process and from what activity the link is posted.

4.4. Requirements Management

The following chapter aims to describe and clarify the process the company used to get from the start of the Giraffe AMB development project to a finished developed system ready for production, with a focus on the maintainability aspects. Important areas are how the maintainability requirements were created, updated, implemented and finally verified.

The realisation process presented in this chapter describes how the company generally works with the distribution of the different requirements for a system and how the created designs are reviewed against them. However, dividing the requirements into different subsystems is just the beginning. In an iterative process the requirements are updated and more are added as the project progresses from the conceptual phase in the beginning and moves towards the physical phase which finally results in a finished system. This means that the requirements set in the beginning are not all fixed. Depending on the amount of design work being conducted it is also not a certainty that subsystem designers work from an existing design specification, which purpose it is to explain how the design should be performed to fulfil the requirements. Instead they might very well be looking at older but similar designs without even having a design specification in the conceptual phase. The information they have received is often of informal character describing what work needs to be performed.

The processes described previously in this chapter may seem to be carried out in a serial sequence but in reality it is an iterative process between the different departments in project teams. Requirements are allowed to evolve as the development progresses and as the team learn more about the feasibility of the target requirements in terms of cost, resources and time.

Handling the Initial Phase of Development
As a result of a lack of clearly defined requirements in the beginning of the development process, especially the conceptual phase, much of the development is defined by the general understanding of the system, or at least subsystem, that the people designing the system have. According to an ILS manager interviewed it is also important from a maintainability-point-of-view that there exist good communication and an open dialog of which different design decision that are made, especially between the Mechanics and Environment Department and the ILS Department. Failure to achieve this may led to important design decisions being taken without sufficient background maintainability information being considered.

4.4.1. Requirements Creation

The top level requirements that exist on maintainability are constraints rather than requirements, see Appendix A for an excerpt from the requirement specification for the enclosure that applies on this case study. The constraints are broken down and adapted to the different parts of the system to be of use. The process that the company used to do this in the development of the Giraffe AMB system will be described in this subchapter. The different documents that were created during this process are shown in Table 4-3.

Table 4-3 - Specification and requirement documents

Doc. No.	Doc. Type	Description
1029	Requirement Specification	What the system should do.
102 62	Design Specification	How the system should fulfil the requirements.
1559	Requirement Distribution	How the requirements are divided to the subsystems.

The c*ustomer specification* (outside the scope of this thesis) describes the performance that the product should have. Input to the customer specification can generally come both from customers as well from within the company as stated earlier. The customer specification is created by the Product Management Department. When they have completed their work the specification is passed on to the Systems Design Department that creates a *requirement specification* that governs the complete product (see Figure 4-2). In the requirement specification the maintainability requirements are defined.

To simplify the development process the product's different requirements are delegated to the different *subsystems*. This is done by the creation of a *requirement distribution* document that describes what requirements belong to which subsystem (see Figure 4-2). It is up to the engineers in that subsystem to create the *design specification* describing *how* the system is to be designed to fulfil the requirement specification.

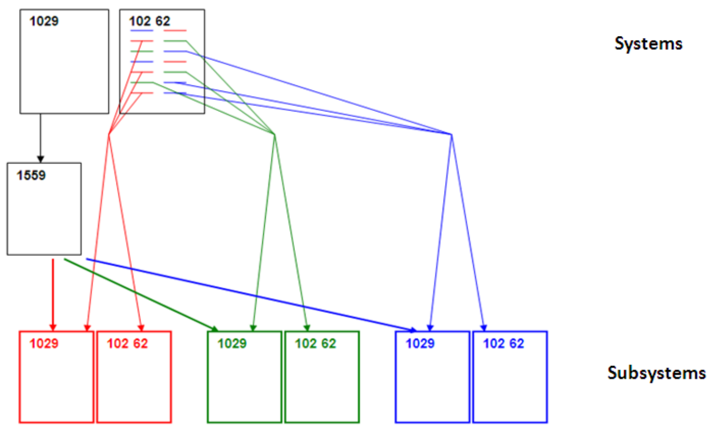

Figure 4-2 Requirements process - a company internal description of the relationship between requirement and design specifications

4.4.2. Requirements Review

During the design process several reviews are held to ensure that the design being created is in accordance with the specifications available, and that all the necessary steps are being performed. There are three main types of reviews (note that the description of the reviews below is made at a fundamental level and is not to be considered as complete);

Design Review (DR)

Basically a tollgate event where a checklist is reviewed to make sure that the product has achieved the desired status. Criterions that are judged are:

- That the appropriate knowledge and information is available to support further development.
- That the quality of the product and its documentation meets the requirements.
- That the defined work process has been followed.

Technical Review (TRW)

Review of the component or product being developed. Depending on which phase of development the product is in different things are included in the review such as drawings, CAD-models, mock-ups, prototypes etc. These are audited against the requirements and specifications available. The review follows a pre-determined checklist with many different topics. Next to each topic there is a status box with three alternatives: Yes/No/Not Applicable (see Figure 4-3). Topics that in some way can be related to maintainability are:

- Review of EEH-reports from previous manufacturing of the unit or from components from which design has been used.
- Review of installation and manageability which in turn refers to the document with instructions for mechanical design (see 4.5.1).

- Service and maintenance.
- MTBF.

1.5	**ÅTKOMLIGHET**	**JA / NEJ / N.A.**
A	Installation och hanterbarhet *(ref. 1020-FCK11540)*	
B	Service och underhåll	
C	Kontakter	
D	Förbrukningsartiklar *(ex filter)*	
E	Luckor dörrar	
F	Fastsättning av enhet	
G	Skyltar Kontrollera att åtkomlighet finns vid avläsning med streckkodsläsare vid installation *(mot systemmodellen)*.	

Figure 4-3 - Excerpt from TRW-checklist (Swedish)

The TRWs do not work as well as they should do. An invitation with the review material for a TRW meeting must be received by the attendees at least two weeks in advance. However, there is a varying degree of preparation before the meetings by the attendees and it is entirely up to them of how detailed the review becomes.[12] In the final report for the Giraffe AMB 1 subproject enclosure[13] it was also stated that the TRWs have sometimes had a more information meeting character rather than being a review. It is suggested that reviews should be done more detailed and be given more time. It also recommends that the internally called “buddy reviewing” should be practiced to a greater extent, that informal reviews like this reduce errors.

Hardware Review (HWR)

This review is conducted in the physical phase of the development when there is a real product to review. It focuses on issues related to the production of the product. Production aspects are often considered in TRWs conducted earlier but not to the same extent.

In the final report for Giraffe AMB 1 subproject enclosure[13] mentioned above the HWR are criticised for not functioning properly. They were conducted too late in the development and the feedback was of very low quality which resulted in many iterations.

4.4.3. Requirement Verification

Before delivering the product to the customer the Integration & Verification Department (I&V) ensures that the requirements that were set have actually been met. They can be seen as an *internal customer* and they set up the verification specification after the requirements specification is

[12] Design Engineer interviewed by: Ericson, J. & Andersson, E. (11th February 2013)
[13] Document number: 03621-M/FCP1041264

created. The verification specification is used to communicate to the customer that the expected quality is delivered and what methods have been used to test it.

To verify maintainability requirements, MTTR, MTBF and MTBCF, ILS produces reliability and maintainability reports. The input to these reports varies for different components. In some cases a maintainability analysis might have been performed, in which case the MTTR value of the component has been physically tested. If this is not done then ILS makes predictions instead.

Predictions of MTBF and MTBCF values are based on experience of using the same or similar components in previous systems. An ILS expert referred to the way of working as "qualified guesses", where naturally the amount of experience affects the quality of the prediction. Some components might have a long service record and because of that accurate predictions of their performance can be made, whilst others might be completely new and as a result the prediction for those units comes with a higher degree of uncertainty.

The prediction of MTTR values are carried out in a similar manner as for MTBF and MTBCF. ILS service experts try to estimate the time it takes to repair the different components in a unit. They might ask the engineer responsible for the design for his or hers opinion. The ultimate way of doing this would naturally be to conduct the actual repair work in real life, as is the case in a maintainability analysis, but due to time and cost reasons this is rarely done unless it is a direct demand from the customer.

There is usually a representative from verification in the project management group from the project start. Depending on the size of the project different subsystem areas can also have a representative each in the project management. During the product development process verification representatives examine design specifications and are only officially involved during the design review meetings. These meetings are often too short to cover everything that needs to be reviewed and the meetings are dependent on the attendees' preparations and activity. Maintainability can be difficult to evaluate from CAD-drawings or specifications and the quality can therefore vary and not be discovered until late in the production phase. Unofficially, individuals from verification visit the subsystem designers to discuss issues that could present a problem and should be addressed from the beginning. However, these meetings are dependent on the verifier's knowledge of who designs the specific components and also the experience to recognise future verification problems. Since it is not an official task time becomes an issue but the meetings usually yield good results.

4.5. Supporting Methods

Three supporting methods that the authors have investigated and are relevant to the topic of maintainability are mentioned in this section; Design guidelines, FMEA and a lean A3 design specification.

4.5.1. Design Guidelines

To assist and guide the engineer in the development work there are guidelines for the engineer to follow when working with mechanical design. The guidelines are a list of "best practices"-principles that must be used at the company. In the document *Instruction for mechanical design*[14] there is a very short chapter about serviceability consisting of two guidelines:

- Geider installation should be used whenever possible to facilitate the serviceability and installation of units.
- Consideration should be taken to ensure that the required space for service and maintenance exists between components and units.

The needs to standardise what different types and sizes of screws that are used in the company's products have been expressed by a Customer Educator[15] as well as a Systems Verification Engineer.[16] In the design guidelines suitable sizes and types for different situations are described. However this lets the engineers choose between a very wide range of components with the result that many different sizes are used, which in turn requires many different tools for assembly, disassembly, repair and service. A System Engineer[17] expressed the need for some sort of instruction or guidelines for how to design for maintainability. The System Engineer also mentioned the possibility of having short courses in the subject for the design engineers.

4.5.2. FMEAs

During the development work of the Giraffe AMB 1 no FMEAs were conducted according to an ILS expert.[18] Instead, FMEAs were conducted when the development was complete as a method to analyse the end result.

The FMEA team was made up of at least one ILS representative who was responsible for the FMEA and who handled the administrative work of conducting the method. The other members of the team were engineers, including a subsystem engineer, who had deep knowledge of the design being audited, combined with an understanding of the context that surrounded it. In some cases the ILS Department felt that they had sufficient knowledge of the design and chose to do the FMEA themselves and involve the engineers to verify the results in the end.[18]

It is first in recent years that FMEAs has started to be used as an aid in the development phase, a result of a larger focus on increasing the MTBF and in particular the MTBCF values of the products being developed.

4.5.3. Lean A3 Design Specification

In recent years an addition has been made to the different requirement and specification documents, the Lean A3 design specification (see Figure 4-4). Its purpose is to give the design engineer better support and background information during the development phase of a unit. This is accomplished by further explaining the general design specifications in more detail for each unit. According to an ILS manager[18] the A3 design specifications have been a great improvement to the development. However, it could be brought further up to a system level much earlier in the process

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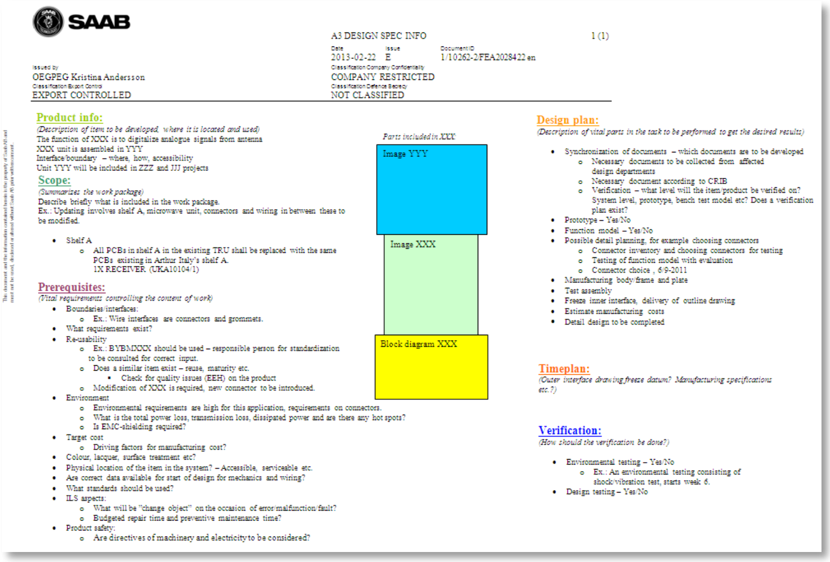
[14] Document number: 1020-FCK11540
[15] Customer Educator interviewed by: Ericson, J. & Andersson, E. (28th February 2013)
[16] Systems Verification Engineer interviewed by: Ericson, J. & Andersson, E. (13th May 2013)
[17] Systems Engineer interviewed by: Ericson, J. & Andersson, E. (19th April 2013)
[18] ILS Manager interviewed by: Ericson, J. & Andersson, E. (22th February 2013)

to plan for maintainability better. Being able to visualise an outline of a system and its intended positioning of components and units provides a better overview and can trigger better solutions earlier. However, it is difficult to plan for something if you do not know what to do.



SAAB

A3 DESIGN SPEC INFO 1 (1)

Date 2013-02-22 Issue E Document ID 1/10262-2/FEA2028422 en

Issued by OEGPEG Kristina Andersson

Classification Company Confidentiality COMPANY RESTRICTED

Classification Export Control EXPORT CONTROLLED

Classification Defence Secrecy NOT CLASSIFIED

Product info:

(Description of item to be developed, where it is located and used)

The function of XXX is to digitalize analogue signals from antenna
XXX unit is assembled in YYY
Interface/boundary – where, how, accessibility
Unit YYY will be included in ZZZ and JJJ projects

Scope:

(Summarizes the work package)

Describe briefly what is included in the work package.
Ex.: Updating involves shelf A, microwave unit, connectors and wiring in between these to be modified.

- Shelf A
  - All PCBs in shelf A in the existing TRU shall be replaced with the same PCBs existing in Arthur Italy's shelf A. 1X RECEIVER (UKA10104/1)

Prerequisites:

(Vital requirements controlling the content of work)

- Boundaries/interfaces:
  - Ex.: Wire interfaces are connectors and grommets.
- What requirements exist?
- Re-usability
  - Ex.: BYBMXXX should be used – responsible person for standardization to be consulted for correct input.
  - Does a similar item exist – reuse, maturity etc.
    - Check for quality issues (EEH) on the product
  - Modification of XXX is required, new connector to be introduced.
- Environment
  - Environmental requirements are high for this application, requirements on connectors.
  - What is the total power loss, transmission loss, dissipated power and are there any hot spots?
  - Is EMC-shielding required?
- Target cost
  - Driving factors for manufacturing cost?
- Colour, lacquer, surface treatment etc?
- Physical location of the item in the system? – Accessible, serviceable etc.
- Are correct data available for start of design for mechanics and wiring?
- What standards should be used?
- ILS aspects:
  - What will be "change object" on the occasion of error/malfunction/fault?
  - Budgeted repair time and preventive maintenance time?
- Product safety:
  - Are directives of machinery and electricity to be considered?

Parts included in XXX:

Image YYY

Image XXX

Block diagram XXX

Design plan:

(Description of vital parts in the task to be performed to get the desired results)

- Synchronization of documents – which documents are to be developed
  - Necessary documents to be collected from affected design departments
  - Necessary document according to CRIB
  - Verification – what level will the item/product be verified on? System level, prototype, bench test model etc? Does a verification plan exist?
- Prototype – Yes/No
- Function model – Yes/No
- Possible detail planning, for example choosing connectors
  - Connector inventory and choosing connectors for testing
  - Testing of function model with evaluation
  - Connector choice , 6/9-2011
- Manufacturing body/frame and plate
- Test assembly
- Freeze inner interface, delivery of outline drawing
- Estimate manufacturing costs
- Detail design to be completed

Timeplan:

(Outer interface drawing freeze datum? Manufacturing specifications etc.?)

Verification:

(How should the verification be done?)

- Environmental testing – Yes/No
  - Ex.: An environmental testing consisting of shock/vibration test, starts week 6.
- Design testing – Yes/No

Figure 4-4 A3 - design specification template

The lean A3 design specification includes several headlines with areas to considered that are not covered in the previously used design specifications such as; time plan, verification plan, prerequisites and design plan. These were previously kept in separate documents unreferenced to the design specification. This means that the lean A3 design specification includes references to documents covering as many design aspects possible. Relevant aspects to the master thesis topic can be found under the prerequisites headline on the A3 design specification:

- Physical location of the item in the system? – Accessible, serviceable etc.
- What standards should be used?
- ILS aspects:
  - What will be "change object" on the occasion of error/malfunction/fault?
  - Budgeted repair time and preventive maintenance time?

Under the headline design plan the development aspects that are crucial for the end result are described, such as the possible creation of prototypes and functional models. The existence of physical prototypes makes a big difference to determine to what degree maintainability has been reached in the on-going development phase according to interviewed designers, verifiers and ILS experts. Finally under the verification headline the chosen methods of verification are stated. Which methods that are chosen can have a big impact on the quality of the verification of the maintainability requirements.

During the creation of the lean A3 design specification the ILS Department were given the possibility to contribute with topics that concerned maintainability, but with a maximum of two sentences. The limitation of only having two sentences was restricting and ILS would have liked to incorporate a few more into the specification.[19]

4.6. Equipment Room – Investigation

The equipment room located in the Giraffe AMB, as shown in Figure 4-6 and Figure 4-5, was the first step to narrow down the case study to a more in-depth and applicable area.

Figure 4-6 Giraffe AMB

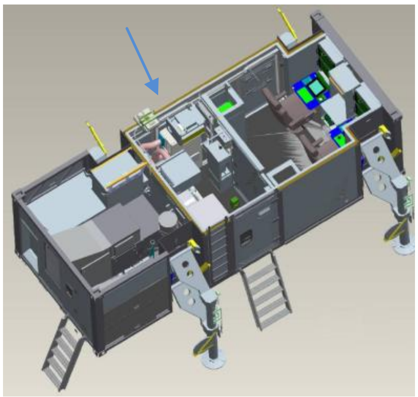


Figure 4-5 Giraffe AMB - the equipment room

4.6.1. Equipment Room - Units Description

The following units are included in the selected area of investigation; the equipment room.

ECU - Electronics Cooling Unit	Delivers conditioned air for the cooling or heating of the TRU and the SDU.
ACU - Air Conditioning Unit	Delivers conditioned air for controlling the operator's environment to the operator room and to the equipment room.
TRU - Transceiver and Receiver Unit	Creates and receives the radar signals. Weighs about 200 kilos and is very difficult to replace without custom made lifting equipment (acc. to a service worker at SAAB AB).
TCU - Turntable Control Unit	Controlees the operation of the turntable onto which the radar unit is mounted at the top of the radar mast. Sends information on the current angle of the turntable to the SDU so that it knows in which direction the radar pulse is being sent out. This is absolutely crucial to know in order for the radar to work properly.
SDU - Signal and Data Unit	Acts as the brain of the radar system. All calculations are conducted within this unit.

[19] ILS Manager interviewed by: Ericson, J. & Andersson, E. (23th April 2013)

	Works together with the TRU and TCU.
PDU - Power Distribution Unit	Two units, one handling high voltage from the generator and one works at the 28 volt level.

4.6.2. Equipment Room - Evaluating Maintainability

With the equipment room in the Giraffe AMB chosen as the area to be studied, work of locating critical areas and parts was initiated. A prime goal was to locate a unit that could be used as a base for further research of the maintainability aspects of the product development process used at the company.

As a first stage in the maintainability evaluation the Failure Mode Effect (FMEA) analysis that had been carried out by ILS after the development projects completion was studied (see theory chapter 2.1.3 for more information on the method). The FMEA was focused on different subsystems like Cooling/ventilation or Antenna, but these were not as interesting to the current case as the actual modules or boxes that house the different parts. In an effort to work around this the different subsystems where grouped together depending on in which box most of the involved parts were located, the result was interpreted and can be seen in Table 4-4.

The values that have been used do not come from the investigated version of the Giraffe AMB because these values were not accessible at the time of the maintainability evaluation. Instead values from a later version was used, however the difference in the values are only marginal according to an ILS manager.

The effects (influence) are given in three different levels:

1. Critical. Given when the total radar function is out of order.
2. Degraded. Loss of a non-critical function or reduced performance of the radar.
3. Minor. Limited affect on the system and it is less than Degraded.

Table 4-4 - Failrate analysis

Unit	Subsystems included	Failrate Critical	Degraded	Minor	MTTR Subsystem
Signal and Data Unit	Data Processor	99,7	9,1	35,6	44,27
	Radar Control	35,1	2	2	28,18
	Signal Processor	21	135,3	23,4	23,76
Sum:		155,8	146,4	61	
% of total:		36	77	52	
MTTR Unit [min]:					32,40
Trans. Rec. Unit	Transmitter	117	5,5	2,4	91,24
	Wave Guide Unit	15	3	0	120
	High Frequency Function	56	4,2	3,8	32,57
		188	12,7	6,2	
% of total:		43	7	5	
MTTR Unit [min]:					75,61
ECU/ACU/LCU	Cooling/Ventilation system	32,1	20,8	14,1	102,12
% of total:		7	11	12	
MTTR Unit [min]:					102,12
Turntable Control Unit	Turn Table System (inc TT)	16	0	18,5	69,42
% of total:		4	0	16	
MTTR Unit [min]:					69,42
Power Distribution Unit 1+2	Power supply and Cabling	40,4	10,4	18,2	41,41
% of total:		9	5	15	
MTTR Unit [min]:					41,41

One of the main reasons for investigating the FMEA analysis was to try to create a picture of what units that was fail-intensive, and thus has a bigger need for service and repairs, combined with the MTTR for the different units. Of high interest was to try to locate a suitable unit to use for further investigation in the thesis work. Another interesting aspect was how the maintainability of the different units had been prioritised in the equipment room compared to their respective failrate and MTTR values.

As can be seen in Table 4-4 the most fail intensive units are the SDU and TRU, which is not a surprise since these two are both complicated units made up of a lot of different components. However, they are designed in a way which enables them to be repaired relatively easy by removing the front panel of the units which contributes to keeping the MTTR quite low, especially for the SDU which basically is a big computer made up of easily exchangeable parts mounted in racks. The two units have also been placed in the equipment room in such a way that other units do not interfere when repairing them and they both have good built in abilities for diagnosis which also contributes to a low MTTR. The two PDU units are designed in a way that enables them to be pulled forward and tilted down, giving access to the unit from its top. This design makes the units easy to repair which contributes to a low MTTR. The MTTR value for the TCU is not very accurate because the TurnTable Unit (TTU), which is not located in the equipment room, is integrated in the value and is a major contributor to the failrate and MTTR values. This is made clearer when reviewing the Logistic Configuration Baseline (LCB) for the Giraffe AMB and the section about the TCU which is shown in Table 4-5.

Table 4-5 - Censured excerpt from LCB for Giraffe AMB 1 - TCU

Denomination	QTY SYST	Failrate	MTTR
TURN TABLE SYSTEM			
TURNTABLE CONTROL UNIT			
Component 1	1	2,5	45
Component 2	1	1,5	45
Component 3	1	0,1	45
Component 4	1	3	45
TURN TABLE			
Component 1	1	0,5	45
Component 2	1	8	70
Component 3	1	1	60
Component 4	2	5	80
Component 5	2	5	80
Component 6	2	4	80
Component 7	2	4	80

Looking at the table it is clear that the seven components in turn table stands for a major part of the failrate and is responsible of increasing the MTTR value for the entire turn table system. A more accurate value for the turntable control unit alone is probably around 45. Regardless of the exact MTTR value the TTU it is a product that is bought from a suppliers and has not been developed by the company, which disqualifies it from being an interesting unit to investigate further.

One of the reasons for investigating the FMEA analysis was as stated earlier to locate a unit to use for further investigation during the thesis work. The type of unit that was sought was a unit with high MTTR but that was relatively simple in its design and could be studied separately from other units. After reviewing the FMEA analysis and consulting with system experts the ECU was located as a unit matching those criteria. Regarding the prioritising of the maintainability of the different units in the equipment room the current solutions appeared to be justified. The review of the FMEA analysis (Table 4-4) together with the units' locations in the equipment room showed that the fail intensive units also where the ones where measures had been taken to improve their maintainability in terms of their design and location in the equipment room.

4.7. The ECU - Electronics Cooling Unit

In this chapter a complete overview of all the specifications and issues of maintainability regarding the selected unit will be presented; the ECU.

4.7.1. The ECU - Specifications

With the ECU selected as the unit to be investigated further from a maintainability perspective the first stage was to review the maintainability requirements that were put on the unit during the development process. Requirements and other factors that influenced the design of the ECU will be covered in this chapter.

In one of the design specifications[20] for the Giraffe AMB it was stated that the ECU for the system should be the same unit as used in an Arthur system, a mobile Artillery Hunting Radar, cooling system. This means that the cooling unit itself was not intended for use in the Giraffe AMB when originally designed. However, in an effort to try to minimise the number of different parts the company uses the unit was chosen to be used in the Giraffe AMB 1. To adapt the ECU to the Giraffe AMB a small project of 220 hours was planned, more on this in the next chapter.

The ECU - Project Specification and Time Plan

The time plan for the Giraffe AMB subproject for the Enclosure Department in 2007, today renamed to Mechanics and Environment Department, can be seen in Figure 4-7.

The timespan for the development project ran from October 2005 to March 2007 from which the Giraffe AMB 1 ended with a customer delivery in March 2010.[21] Specifically for the ECU the planned time was set from May to September 2007 but did not fulfil its required reviews until December that same year. This was caused by the reuse of the ECU from another development project, Arthur, and thereby inheriting its faults that had not yet been found and reviewed. The reuse was thought to go swiftly and without much trouble since the placement of the units would be very similar. However due to problems with leakage in the air ducts additional work had to be done before the ECU and its air ducts was successfully adapted to the Giraffe AMB. The resources original planned for the adaptation of the ECU to the Giraffe AMB was 220 hours according to a project planner. With the need for additional work the total time spent finally amounted to 1258 hours, almost *six times more* than originally planned.

[20] Document number: 10/10262-UAZ10170/25
[21] Project Planner interviewed by: Ericson, J. & Andersson, E. (18th March 2013)

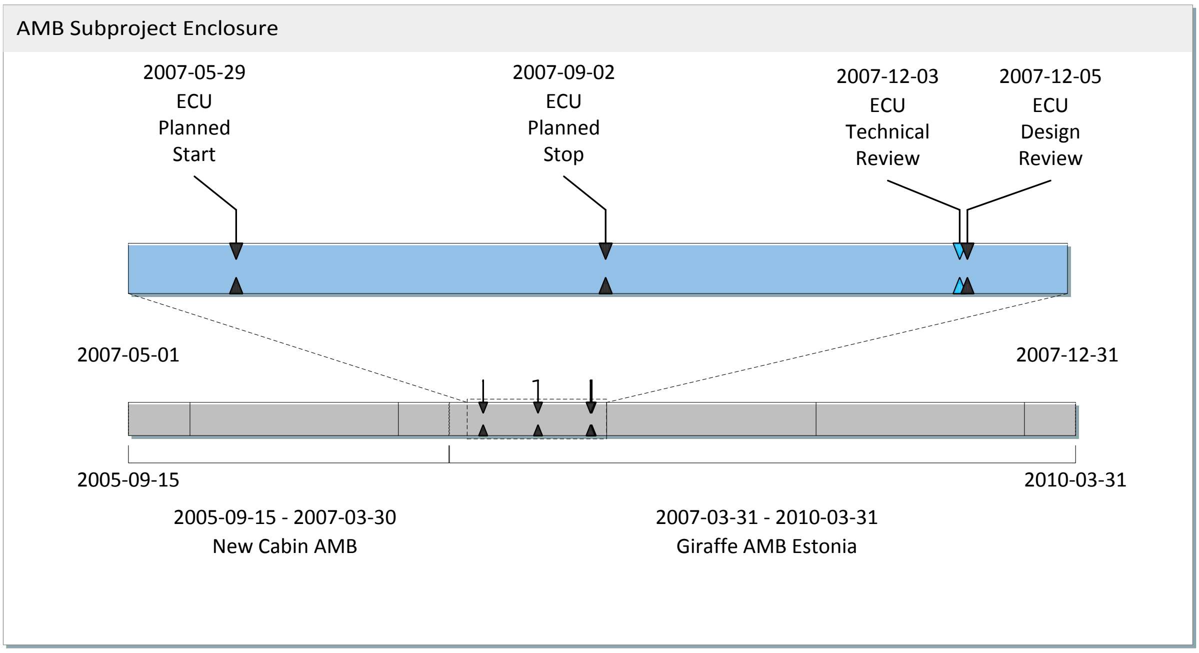


Figure 4-7 Time plan for the adaption of the ECU from Arthur to Giraffe AMB

The time plan is based on the project specification and can be found in IFS, released in 2007. However, by informally asking questions to project members the authors discovered that there was more detailed information to be found in the project folder still available on the company's project areas. This document was not released or uploaded in a preliminary version in IFS but was discovered at an informal meeting.

Table 4-6 The project specification versions

Type	Doc. No.	IFS (Y/N)	Rev.	Comment
Project Specification	12702-M/FCP1041264	Y	A	Released 2007-05-28
Project Specification	12702-M/FCP1041264	N	N/A	Newer version found in the project folder, requires access

The ECU - Requirement Specification

The requirement specification for Giraffe AMB 1 is divided into different documents depending on which part of the system it regulates. In the requirement specification for Giraffe AMB 1 ENCLOSURE[22] the requirements that dictate the performance of the enclosure system are stated. The ECU is one of the vital components in the enclosure system.

In the requirement specification there were no requirements on the ECU's performance abilities', instead these functions were described in the design specification in the section below. In the Giraffe AMB project the maintainability requirements were not divided between different units or subsystems. Instead requirements on values for MTTR and MTBF for the entire system in total were stated (see Appendix A).

[22] Document number: 2/1029-UAZ10170/25

The ECU - Design Specification

In a similar way as with the requirement specifications, the design specifications are divided into different documents regulating the functions of different part of the Giraffe AMB 1 system. In the design specification for *Giraffe AMB Enclosure*[23] the maintainability prerequisites for the entire system, mentioned in the section above, were divided into different subsystems. One of those subsystems was the ECU and its values were as shown below in Figure 4-8.

MTBF	MTBCF	MTTR
• 24 000 h	• 26 667 h	• 50 min

Figure 4-8 The maintainability prerequisites from the design specification[23]

In the design specification for the *Giraffe AMB Enclosure Climatic System* [24] detailed characteristics of the ECU were stated such as:

- Weight
- Dimensions
- Capacity for cooling and heating
- Power consumption
- Air filtration in the air ducting to the TRU/SDU
- Drainage for condensed water with outlet interface matching the one in the shelter

The requirements on the mechanical interface stated that the ECU should be able to be mounted on the shelter wall in the equipment room, directly below the ACU. There were also a general requirement that all connections for pipes and hoses should be easily accessible for mounting and dismounting. This was the only requirement that gave any guidance of how the maintainability prerequisites should be fulfilled. The specifications that existed on the air ducts from the ECU to the TRU/SDU stated that they should incorporate an air filter and that the noise level from the ECU together with the air ducts should not surpass a certain dB level.

4.7.2. The ECU - Maintainability Issues

The Logistic Configuration Baseline (LCB) for the ECU lists articles that require corrective or preventive maintenance activities. Included in the list are the fan motor, heating elements, a thermostat, an EMI-filter and contactors. Of all of these, only the contactors are possible to replace without removing the entire ECU from its assembled position in the equipment room. This being the case, the time it takes to remove the ECU has a direct impact on the MTTR value on all of those articles except the contactors. Worth to be noted is that according to a Customer Educator[25] the entire ECU unit is always considered to be a replacement unit when instructing technicians operating

[23] Document number: 10/10262-UAZ10170/25
[24] Document number: 14/10262-UAZ10170/25
[25] Customer Educator interviewed by: Ericson, J. & Andersson, E. (22th February 2013)

the Giraffe AMB at the customer location. The choice of the level on the replacement units can differ between customers according to an ILS manager[26], often depending on in which situation the product is being used.

If the product is used in an actual armed conflict then high availability is often prioritized and fast repair times are favoured instead of low repair cost, which in turn leads to bigger pieces of the faulty unit being replaced. In the case with the ECU this means that if for example the fan motor is broken the entire ECU is replaced and the old one repaired offline. This can be compared to the cheaper alternative of removing the ECU and replacing the defect fan motor with a new one before reassembling the same ECU. This procedure will take longer time but is significantly cheaper in terms of the cost of replaced parts.

Regardless of which level of replacement unit that is chosen by the customer, the time to remove the ECU has a direct impact in the MTTR. This is also visible in the individual MTTR values for the articles in the LCB, the articles that requires the ECU to be removed all have much higher values (shaded components in Table 4-7). The values below are from a later version of the Giraffe AMB, the GIRAFFE AMB 2.[27] Compared to the values for the investigated version these are significantly higher, even though the design is more or less identical. The reason for this is because after the first project a maintainability analysis was performed and the values adjusted to better represent the real values. Therefore these seemed more appropriate to present in the thesis.

Table 4-7 Censured excerpt from LCB for Giraffe AMB 2 - ECU

Denomination	QTY SYST	Failrate	MTTR
Cooling Unit Electronics			
Component 1	1	0,3	55
Component 2	2	0,4	55
Component 3	2	0,4	55
Component 4	1	0,3	55
Component 5	1	5,0	160
Component 6	16	0,25	160
Component 7	2	0,25	160
Component 8	16	0,25	160
Component 9	2	0,25	160
Component 10	16	0,25	160
Component 11	1	0,3	160
Component 12	2	0,3	170
Component 13	1	0,2	135

When the removal of the ECU had been recognised as a key performance driver for the MTTR values for most of the components inside the ECU, work began with analysing what affected this procedure the most. After interviews with numerous people in different departments a fairly clear picture had

[26] ILS Manager interviewed by: Ericson, J. & Andersson, E. (29th January 2013)
[27] The full name has been replaced with a 2 for confidentiality purposes.

been created of what the main problem was with the removal of the ECU, and that was the removal of the air duct connecting the ECU with the TRU and SDU. This issue will be described in more detail in the following chapter.

The ECU - Connecting Air Ducts

The air ducts that connects the ECU with the TRU and the SDU is visible in Figure 4-9, with one of the most troublesome part highlighted in blue.

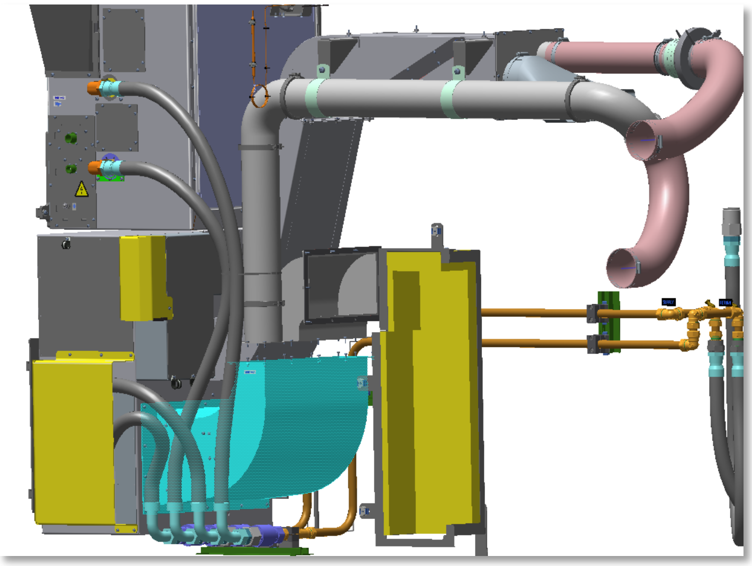


Figure 4-9 Cooling system overview, original design of air ducts

In Figure 4-10 a closer view of the original design of the air duct is shown. As can be seen, the connection towards both the ECU to the left and the next part of the air duct system the model contains a lot of screws. This design might not seem that troublesome at first glance but taken into consideration that the space where it is mounted is limited and that it is surrounded by units on two sides and a wall on the third the problems of disassembling it becomes more evident.

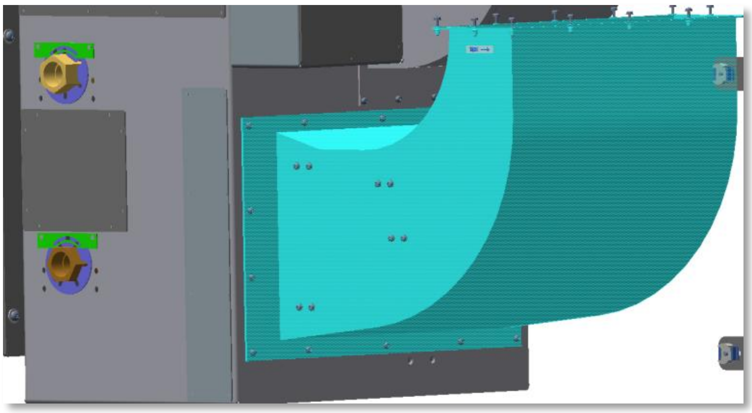


Figure 4-10 The old air duct

Actual experience of disassembling the unit speaks of times up to 8 hours just to be able to remove the air duct. This is of course a problem because as mentioned above the MTTR for the ECU is 50 minutes and according to a Customer Educator[28] the entire ECU is always removed from the Giraffe when repaired, thus completing the repair in 50 minutes becomes impossible. According to experts with experience from assembling the air ducts in production[29] they could be extremely difficult to get to fit. Another dimension was that some of the screws were located in places that were very hard to reach which resulted in that they were disregarded completely. In an effort to resolve the issue with the air ducts a redesign of them was eventually made in a different project and the result can be seen in Figure 4-11. The cost of the redesign mounted to a total of 385 man hours.

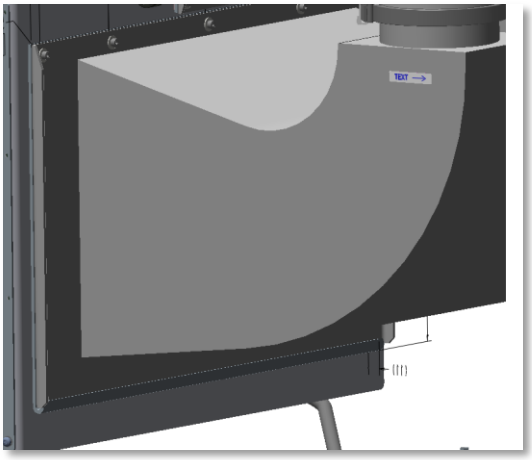


Figure 4-11 New air duct

The most visible change in the design is that the number of screws has been greatly reduced in the interface towards the ECU and completely removed in the top interface. The removal of the rubber bellow in the top interface and the introduction of flexible tubes in its place greatly improved the flexibility of the design and thus made assembly much easier (see Figure 4-12). There had been big issues with getting the different interfaces to line up with each other in a correct way with the previous design.

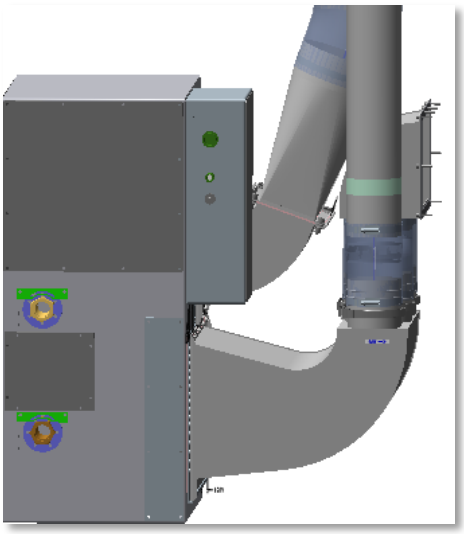


Figure 4-12 New air duct overview

[28] Customer Educator interviewed by: Ericson, J. & Andersson, E. (22th February 2013)
[29] Assembly worker interviewed by: Ericson, J. & Andersson, E. (11th March 2013)

4.7.3. The ECU - Review of the Maintainability during the Development

During the development of the air ducts one technical review (TRW) was conducted with the method described in chapter 4.4.2 and as can be seen in Figure 4-3 serviceability is part of the TRW-checklist. All components were approved, although some required changes first. To which extent maintainability was reviewed is very difficult to assess but an ILS manager was present at the review. An attempt to map out the different reviews conducted has been done for both the air ducts and the ECU and the findings are presented in Table 4-8 and Table 4-9.

Table 4-8 Reviews conducted of the air ducts

Type	Doc. No.	Revision
Technical Review	1/17763-NTM190220/1	B
Hardware Review	1/17764-NTM190220/1	B
Design Review	1/1776-NTM190220/1-1	A

Table 4-9 Reviews conducted of the ECU

Type	Doc. No.	Revision
Technical Review	1/17763-UFD10233/1	C
Hardware Review	1/17764-UFD10233/2	B
Design Review	2/1776-UFD10233/2-2	A

4.7.4. The ECU - Final Verification of the Maintainability

In this chapter the process that was used to make the final verification of the maintainability of the ECU implementation in the Giraffe AMB 1 will be described. Responsible for the verification of the requirements was the Integration & Verification Department (I&V).

As mentioned in chapter 4.7.1 there were no requirements on maintainability except for the entire system as a whole. The following maintainability prerequisites for the ECU were stated in the design specification:[30]

MTBF	MTBCF	MTTR
• 24 000 h	• 26 667 h	• 50 min

Figure 4-13 The maintainability prerequisites from the design specification for AMB 1 Enclosure[30]

However, these were not requirements and therefore not verified but merely created to act as support in the work to ensure that the maintainability requirement for the entire system was fulfilled. To verify the maintainability requirements I&V ordered reliability and maintainability reports from ILS. These reports contained the result of the estimation and calculation of these values based on the current design. See chapter 4.4.3 for more in-depth description of how the reports are created.

[30] Document number: 10/1029-UAZ10170/25

The reports presented values that passed the maintainability requirements that were put on the system and since I&V's task was to verify the requirements, not the design specifications, they were satisfied with that. Even if I&V would have compared the values in the reports regarding the ECU (see Table 4-10), calculated a MTTR for the unit, compared these with the values in Figure 4-13 and seen that they differed this would not have mattered. In the end what matters to I&V, and not least to the customer, is that the requirements are fulfilled.[31] If the requirement is a customer requirement, which maintainability requirements often are, then their fulfilment is absolutely critical or else the customer won't accept the product.

Table 4-10 Censured excerpt from LCB for Giraffe AMB 1 - ECU

Denomination	QTY SYST	Failrate	MTTR
Cooling Unit Electronics			
Component 1	1	0,3	35
Component 2	2	0,4	35
Component 3	2	0,4	35
Component 4	1	0,3	35
Component 5	1	5,0	70
Component 6	16	0,25	70
Component 7	2	0,25	70
Component 8	16	0,25	70
Component 9	2	0,25	70
Component 10	16	0,25	70
Component 11	1	0,3	70
Component 12	2	0,3	80
Component 13	1	0,2	45

According to one of the project planners[32] the customer of the Giraffe AMB 1 system was aware of that the maintainability of the ECU was poor. However, this was considered acceptable since the unit was predicted to rarely break down and since a low MTTR on the ECU was not a requirement.

[31] Systems Verification Engineer interviewed by: Ericson, J. & Andersson, E. (13th May 2013)
[32] Project Planner interviewed by: Ericson, J. & Andersson, E. (18th March 2013)

4.8. Summary of the Requirements Findings

To summarise the documents traced through the break-down structure the figure below, Figure 4-14, shows their level, their relationship and their contents regarding maintainability. The top level does not contain any mentioning of maintainability but references the requirement specification for the enclosure.

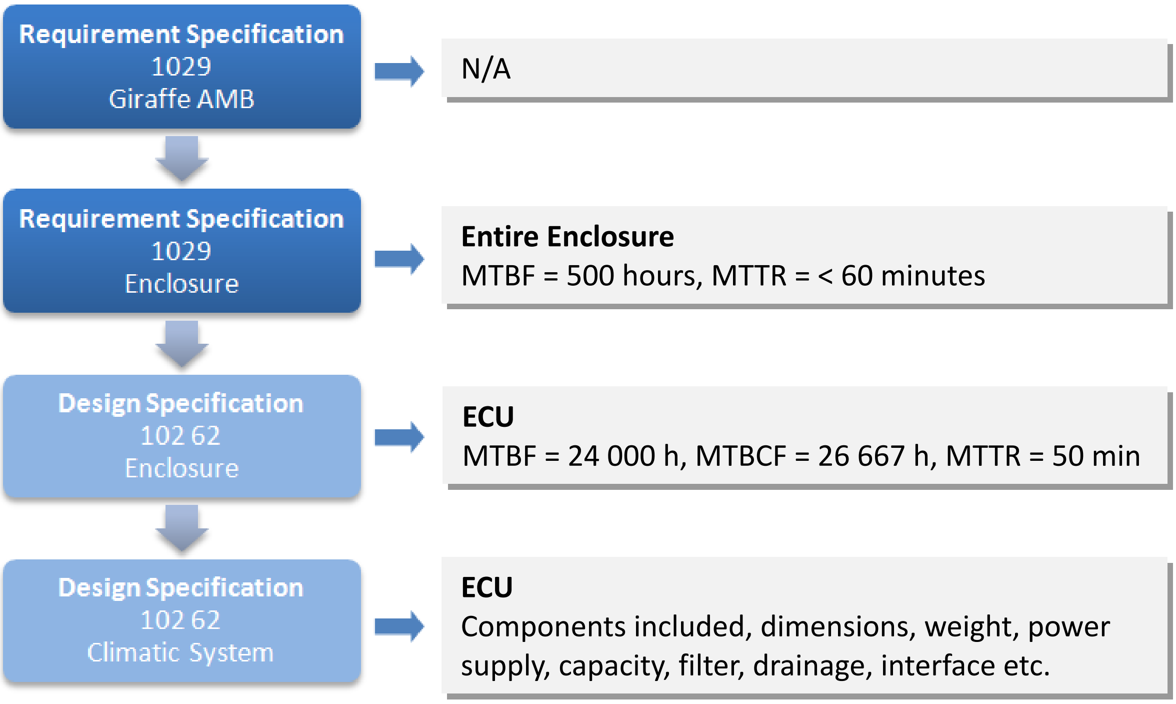


Figure 4-14 The requirement and design specifications together with their content

5. ANALYSIS AND RESULTS

The analysis and results have been combined into one chapter where they are covered one research question at a time; first with the analysis of the research question and then the results of that analysis. This has been the most logical and effective way to present the information and each research question are also divided into two sections; first generally of how the company works and then specifically the ECU.

In this case study the authors have followed a quite simple unit within a larger system, investigating what methods and reviews it has gone through as well as its maintainability issues. The concept of front loading as mentioned in chapter 2.2, and planning as much as possible in the beginning of the development, is not done to any great length at the company today when it comes to maintainability aspects. Many iterations and late changes are done when solutions do not fulfil the requirements. The results of these research questions will hopefully help with this issue and enable an earlier and more integrated method for front loading.

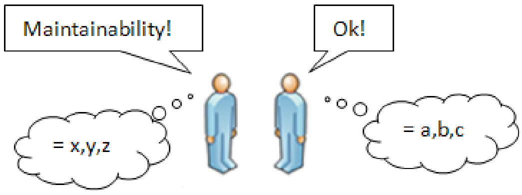
5.1. RQ1 Analysis - Maintainability Requirements

RQ1: How are maintainability requirements created and developed in the product development process?

It should be mentioned that the process of tracing information on requirements in this thesis have been very difficult. Most of the gathered data comes from key people and the information system IFS where revisions and releases are managed. Some documents have been found by coincidence by asking the right person the right thing at the right time. The information system IFS provides several search functions like document number, title, document type etc. but since this case study has stretched over several project numbers (e.g. the number for the Giraffe AMB 1, the ECU, the air ducts) it has been difficult to get a grasp of the whole picture. Just knowing what project number to search for can be hard to find. Different reviews on different levels passing different stage gates are very difficult to put in a process and map out. Hundreds of documents in different revisions have been uploaded to the IFS system and yet some later versions have been found by the authors that only exist in project areas and on employees’ computers. This inconsistency decreases the traceability of changes and updates that happen after a project is considered completed.

5.1.1. The Language and Requirements Formulation

Maintainability is a difficult topic because it deals with constraints of design solutions and can be difficult to formulate. Furthermore, confusion, misunderstandings and uncertainty regarding different engineering terms could be causing some of the problems with keeping a maintainability focus in the development process. Communication and knowledge transfer is difficult between different departments because of the variation of the work tasks and priorities they have. Cross-functional project teams with representatives from several different departments (e.g. mechanics, power, verification) do not necessarily have a common language and often have different priorities. Therefore, clear definitions of terms and jargon are important for the top management to enforce and keep rigid without room for misinterpretation. Deciding what main term to use, serviceability or maintainability, is a natural first step. Both terms are used within the company when referring to the same thing. The thesis authors have as mentioned before chosen to use the term maintainability because the definition seemed more fitting when reviewing the theory on the subject. Using the term serviceability the authors have experience that people tend to think of only plain service issues such as changing filters and oils. Issues concerning the replacement of faulty components seem often to be overlooked.



At the company the term maintainability and its measures of MTTR, MTBF and MTBCF do not seem to be sufficiently communicated to all involved. If a project is run with key words such as simplicity, reliability and maintainability, they need to be clearly formulated and defined to what extent these should be realised. Preferably they should be broken down in more concrete statements on how the design work should reflect these key words. Though the actual formulation of requirements and constraints regarding maintainability does not suffer from low quality; the problem is rather *the lack of them* on subsystem levels. An example of this is the A3 design specifications that are used by the subsystem designers. On the A3 design specifications the template file only mentions maintainability in the statement "Physical location of the item in the system? – Accessible, serviceable etc." but gives no reference or guidance on how or where to find the knowledge on how to accomplish this. Further bullet points on the template as shown in **Fel! Hittar inte referenskälla.** regards maintainability and are listed as "ILS-aspects". Improvement suggestions of the A3 design specifications are given in chapter 5.6.5. Constraints (maintainability requirements) are difficult to write as mentioned in chapter 2.3, especially in a very function-oriented organisation like the company, and should be given more attention on a system level.

5.1.2. Information Confusion

When creating requirements specification and design specifications there are a number of different documents and guidelines that employees can look at. However, information is spread rather wide in several places and it is not obvious where to look to find it. The R&D process, as can be seen in Figure 4-1, is meant to be a tool for the different departments and provides a collection of templates, documents and examples. Despite this attempt to gather all data, several other documents have been created externally (e.g. the "A-Ö lista, MCD Support document") of the interactive and web-based process and it became evident from the interviews that the page did not provide the intended aid. The templates and examples from the process are difficult to find and the process is constructed in such a way that it is difficult to understand the proper order of the product development process and the different sublevels. The subsystem designers do not appear to be aware of the documents they can find there or where documents they do know exist can be found. This work process either causes ignorance of the tools at designers' disposal or a lot of time searching for the right document.

5.1.3. General - Requirements Creation

Requirements are created in their first basic format at the top level in a customer specification. These are then transformed from customer requirements to system requirements and allocated to the different subsystems. Since system requirement specifications are meant to describe *what* is to be done, subsystem design specifications are meant to describe *how* the requirements should be fulfilled. However, the design specifications are not verified, only the system requirements which are very general when it comes to maintainability, as seen in Appendix A.

Regarding maintainability aspects the company chose in the Giraffe AMB case to keep those requirements on a top level only, stating requirements for the system as a whole. In the design specification for the enclosure part of the Giraffe AMB these requirements were broken down on a subsystem level. However, since they then no longer were requirements but maintainability prerequisites their fulfilment was not mandatory. What this means is that as long as the total maintainability requirement on top level was fulfilled, individual units were allowed to deviate from the value stated for them. Of importance for the customer is the maintainability of the entire system and therefore the value for an individual unit is not crucial. Worth to keep in mind is that even though maintainability is measured on the top level, the customer still expects the entire system to have good maintainability and therefore the issues with the ECU and its connecting air ducts was not appreciated by the customer.

Today, as was the case during the development of the Giraffe AMB 1, requirements and verification methods are kept in separate documents. As previously stated in both theory and empirical findings, having a requirement is useless unless you plan to verify it. System requirement specifications could include verification requirements for each statement, how the requirement will be evaluated and what value is acceptable. This topic will be further discussed in research question two.

The entire development phase should always consider both the system functions and the system use. Today, the company seem much focused on system functions rather than system use. From literature there are a number of suggestions on what maintainability practices a company should have during the different life cycle stages, see Figure 2-3 in chapter 2. The new cabin for the Giraffe AMB had a development time of two years but was sold with a life expectancy of twenty years. Since uptime and reliability in the military industry is of high importance the ease of maintenance and service will have a large effect on customer satisfaction and the company brand. As mentioned in theory chapter 2.1 “Designing a good maintainable system is crucial for customer satisfaction and should be characterised by having to requiring as little time as possible for as low cost as possible and as low use of resources as possible.” Therefore, being able to identify what maintainability requirements (constraints) the system should have as early as possible could have significant impact on the commercial success of the system.

5.1.4. The ECU - Requirements Creation

In the ECU-case, which involved the adaptation of the ECU (electronics cooling unit) into the Giraffe AMB, the reuse of an unverified unit resulted in a lot more redesigning than expected. The errors that occurred can be traced back to the lack of defining the maintainability prerequisites to any greater extent than the usual MTTR, MTBF and MTBCF for the entire unit, combined with a very short time plan for the development. In the case of the ECU the unit was lifted from another development project straight into the Giraffe AMB and it was assumed it would require very little adaption to the new system. However, the unit had not been verified or tested in the first project and the problems were inherited to the Giraffe AMB as well. When the unit was brought in the team assigned to its integration in the Giraffe system was not aware of it having any trouble and the project required redesigning in a very late phase in the development. The maintainability of the ECU was not good and it was not possible to disassemble it in the time set in the design specification. Following the system prerequisites on the acceptable values to take the ECU apart nothing was documented on how it should be designed in order to ensure the fulfilment of the prerequisites. There was no description or guidelines for what could accomplish the set values. The ECU had the following values (see Table 5-1) assigned at a system level as well as the parameters and constraints on a subsystem level that will affect the design solutions.

Table 5-1 The ECU's design specifications

Top level	Requirement specification Enclosure Giraffe AMB	MTTR < 60 min MTBF => 500 h
System level	Design Specification Enclosure Giraffe AMB	MTTR = 50 min MTBF = 24 000 h MTBCF = 26 667 h
Subsystem level	Design Specification Climatic System	Weight, dimensions, capacity, power consumption, air filtration, drainage. Connections for pipes and hoses should be easily accessible for mounting and dismounting.

The design specification where the requirements from Table 5-1 are taken from does not live up to the company's description of what it should contain, at least not on a component or unit level like the ECU. There is no indication of *how* the requirements should be fulfilled or met, merely what it has to contain, what basic parameters to consider (though no values) and what support it has to provide. Interviews with subsystem designers have yielded that much of the design is done with common sense. There are few guidelines for what *easy* accessibility for mounting and dismounting really means and it is very difficult to evaluate the user's need from a CAD-model. With this in mind it is perhaps not as hard to believe that removing the air duct connected to the ECU took over eight hours in the Giraffe AMB with the new cabin, making the maintainability prerequisite of 50 min for replacement of the entire unit impossible to achieve.

Requirements on maintainability are difficult to practically interpret and realise. Today these are written in a format that gives the subsystem designer only maintainability prerequisites with the MTTR, the MTBF and the MTBCF in hours for a specific unit. Maintainability values like these requires extensive knowledge and understanding of how the unit operates while in use, how it effects its surrounding units and their respective maintainability requirements and knowledge of how the unit is repaired. Possessing this knowledge without having prior education in the specific topic or experience of the units is difficult.

An example of how maintainability is not taken into consideration is how one interviewee described how they pack the units with components: As much function as possible in a very restricted space sometimes with little consideration of how often the components breakdown (their fairate) or how they are placed. Interpreting MTTR, MTBF and MTBCF as a design engineer is difficult but it can be made easier by breaking them down into smaller time units and tasks. However, this is not practiced at the company today and a suggested solution on how to break down the mean time to repair (MTTR) to a more comprehensible requirement from a design point of view is given in chapter 5.6.1.

5.2. RQ1 Results - Maintainability Requirements

RQ1: How are maintainability requirements created and developed in the product development process?

Before requirements on maintainability can be created there has to be a clear definition of what maintainability is. As mentioned in the analysis chapter the company also uses the term serviceability but the usage of multiple terms creates confusion between different people and departments. The thesis authors suggest that the term maintainability is used and that its definition should be:

> *"The ability of an item to be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair".*
> (U.S. Department of Defense, 2005)

Included in the definition should be not only service issues but also issues concerning the replacement of faulty components and units and preventive maintenance. The same measures as before should be used including MTTR, MTBF and MTBCF, all of which are already implemented at the company.

The topic of maintainability needs to be brought to a higher system level where the focus on function requirements needs to shift to also include the constraints; the maintainability requirements. The importance of making products easy to use, maintain and service should be given much more attention in future projects. The development of radar functionality and accuracy is very important at the company because it is a key selling point to attract the customers. However, long-term use of a system also requires that it can be maintained during its life span (twenty years in the case of the Giraffe AMB) and the reliability and maintainability are also important characteristics that need to receive more attention.

The maintainability requirements are set on a high level but stop being requirements when broken down to the individual units. They become maintainability prerequisites. As long as the actual requirement for the entire system is fulfilled, the units' maintainability prerequisites are irrelevant. To balance the formalisation level of requirements and how far they should be broken down in a subsystem, unit and component level further investigation is required. Is the current way of working sufficient or should a requirement be put more specifically on a unit within the system? Should the ECU have requirements rather than prerequisites? A requirement needs a verification method and today the company does not verify prerequisites. This is discussed further in the results of research question three where prerequisites are treated as requirements with a subsystem verification method assigned. These requirements are not only on a unit but of *the tasks* of repairing the unit.

There are many documents from different places that contain guidelines, templates, checklists etc. that are unevenly used. There is no complete overview of when a specific document should be used and it is not enforced by management. This creates a vulnerability in the company where the quality of the work is dependent on how much time and knowledge of certain documents' existence the employee performing a task has. There does not appear to be a standardised method for working with any of the help documents or to what extend they should be followed. This also presents a risk with the results of this master thesis since proposed improvements might very well just end up as one of the many support documents to be picked up by a curious engineer with extra time.

5.3. RQ2 Analysis - Review and Verification of Maintainability

RQ2: How are maintainability requirements and their fulfilment reviewed during the on-going development and verified in the finished system?

5.3.1. General - Verification and Reviews at Saab EDS

Verification of the system requirements is performed by I&V to ensure that the customer agreement of what the system will deliver is met. Though their main work is conducted after the development phase, they are active during the development process at the review meetings to provide input on the work's likelihood of fulfilling the verification requirements. They attend review meetings to continually evaluate the progress of the development but the aids and tools for this are limited. There are often no prototypes, interactive images or physical components to review. The designs are often only provided on a piece of paper in the form of an image from a CAD-model with additional data presented in a table. Another way of presenting the design is with a live presentation of the 3D-model from a CAD-program, however this is done without any aids or methods to visualize maintainability aspects. The aids to help the reviewers to visualise how service and maintenance operations are to be performed and whether or not it is likely that the maintainability is good enough are therefore very limited. As expressed by several of the interviewees: the review meetings are ruled by those who "scream the loudest" and who champion their causes the most. Evaluating maintainability from predictions of MTTR, MTBF and MTBCF values as well as computer models of units is very difficult, if not impossible. The company should give the reviews more time and conduct more thorough maintainability checks with focus on understandable maintainability requirements. The difficulties with the quality of the reviews were raised both in the interviews conducted and in the final report of the Giraffe AMB 1 subproject enclosure.[33] The hardware reviews and the technical reviews must be improved. It is not sufficient with the checklists currently used and they are done too late and with too little time. By breaking down the MTTR as described in the results of research question three into subtasks of access, diagnosis, replacement, check and align, the measurement will bring the reviewers closer to the end user's situation. An attempt to implement a similar kind of method already exists at the company though whether it has been successful or not is difficult to evaluate. As can be seen in the *Requirement Specification for Enclosure in GIRAFFE AMB System* in

[33] Document number: 03621-M/FCP1041264

Appendix A and in Figure 5-1 below there is a section regarding the subtasks that should be considered.

> The corrective maintenance task is performed at operational level and includes the following subtasks:
>
> - Fault isolation
> - Replacement
> - Alignment and checkout

Figure 5-1 Draft from Appendix A

However, there is no indication on any sublevel that this requirement specification is used in the design specifications drawn up. The authors' improvement suggestion presented later in this thesis aims to lift these subtasks to a more practical and applicable level with some additional subtasks added in.

The problems that exist with low maintainability is not to blame on a specific department, group or individual but can be traced to the changed customer landscape during recent years according to the system verification engineer and ILS manager interviewed. Previously, one of the company's largest customers was the Swedish military where FMV (Försvarets materielverk) ordered much of the systems produced. FMV was very thorough in the demands on verification methods and often required maintainability analyses (like time to disassemble) as verification methods and did not accept maintainability *predictions* alone as a verification method.

As a result, physical verifications are not performed to the same extent as they used to. When there were cut backs in the Swedish military the company had to look towards a more international market with more varying customers, who often did not demand as thorough verification methods. However, relying on maintainability analyses to detect problems with maintainability is not an ideal way of working either since the analyses are conducted when the product already has been produced. If problems are detected and redesign is necessary in a very late stage the cost can be very high, not to mention the risk of failing customer delivery deadlines.

For the Giraffe AMB, the requirements set on the ECU went through despite the poor fulfilment for the simple reason that the customer agreed to buy it anyway as long as the requirement of the MTTR for the entire system was fulfilled. Losing the rigorous checks FMV demanded is therefore a long-term loss for the company where the effects might not be seen directly after a sale but will appear years later as the systems age. Furthermore, when the company was investigating new suppliers to compensate the loss of the cabin supplier for the Giraffe AMB they decided to design much if it themselves. Since much of the technological research and secrecy is put into the radar development the other subsystems are often viewed as support systems for the main component; the radar. However, if the mechanical units causes critical failure and the radar can no longer function, its precision and accuracy means very little to the user and customer.

How can then the systems' reliability and maintainability be improved? The most basic step to take is to ensure that the requirements are verified properly and not approved unless fulfilled. The expense of disassemble and assemble all the different parts and units is deemed too high. What the final cost of customer reported errors, redesign, replacement, service agreement fulfilments, damage to brand name etc. accumulates to is outside the scope of this thesis, though theory suggests that efforts put in the early design phases (before production and customer delivery) is always more profitable than solving problems as they occur, see Figure 2-5 in the theoretical background. Improving the review meetings and the less formal meetings that take place during the development process could be one solution. Mock-ups and prototypes can be used to help the developers from different departments work closer together and get a better grasp of what their work will materialise in.[34,35] Many 3D-model software programs today have support for a so called manikin plug-in which puts a correctly scaled human life-like manikin in the model. When designing for ergonomics and human factors this is often a very helpful tool and gives the designer a better understanding for how the product will be used by a human. Since good maintainability is highly dependent on the time it takes for the user to access and replace the different units and components designers and reviewers can benefit from using similar methods to provide better support at the review meetings.

The verification of the requirements is done as previously mentioned by the systems verification engineers. However, it is only the system requirements that are verified and not design prerequisites. The verification on a system level might be perfectly suitable for functional requirements but this is outside the scope of this thesis and it is from the non-functional requirements the following analysis is made.

As shown in Appendix A there are very few non-functional requirements. The Giraffe AMB is sold with a life-expectancy of twenty years and the development was focused on the functions the system had to have and relatively little of how these functions would be upheld during its life cycle, a common mistake as mentioned in theory (Blanchard, 1991). Verifications are conducted at the end of the product development, a phase where any change will be expensive and time sensitive. Being able to prevent as many errors as possible early in the development is the ideal. The company states that they conduct reviews and informal checks during the development but these are unevenly enforced and have a very varying quality.

The requirements set on a system level also remain on a system level. In documents and in informal speech, requirements are often talked of at subsystem level but this is incorrect. Like the ECU, and its MTTR, MTBF and MTBCF that this thesis often has mentioned, those values are only *design prerequisites*. They are not actually requirements which means that they are not verified either. The

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[34] Mock-ups and prototypes are common terms in the R&D companies and are therefore not further explained. For more in-depth knowledge in the subject the authors recommend Product Design and Development (Eppinger & Ulrich, 2012).

[35] Related to the subject, another master thesis at the company has investigated the possibility of implementing prototypes. "Strategy for using Prototypes in the Product Development Process" (Ankarbranth, Mårtenson, 2013)

only maintainability requirements provided are those for the entire Giraffe AMB enclosure. The rest are prerequisites derived through calculations, predictions and qualified guesses on how to reach the system's total maintainability requirement. Using the right terminology is of course important to avoid misunderstandings but it has also been mentioned that if it is not referred to as a requirement it will not be treated with sufficient attention. Therefore it is not corrected or brought to attention in the daily work.

5.3.2. The ECU - Verification and Reviews at Saab EDS

The review of maintainability during the adaptation project of the ECU and in particular its connecting air ducts was limited. Only one technical review and one design review was conducted in the project that comprised of incorporation and adaption of the ECU and its connecting air ducts into the Giraffe AMB system. This is not necessarily the reason for the problem with the air ducts, but for some reason these issues were not discovered, causing costly consequences in terms of increased time to remove the air ducts, which in turn affected the MTTR of the ECU and the entire system. Theory stresses the importance of conducting effective reviews during the development process as a tool to discover problems early to reduce cost. The alternative is discovering them late in the process or even worse after delivery to the customer, which in both cases can become very expensive and also result in reduced performance of the product. In the case with the ECU the issues with the air ducts were finally solved after a couple of years by redesigning them in a different project, but it required additional resources, resources that could have been saved if the issues had been corrected in the initial project. The cost of the redesign mounted to a total of 385 man hours, not including additional costs that are hard to measure such as damage to brand name.

During the final verification of the ECU there was no practical investigation of the maintainability, instead I&V relied on the maintainability and reliability reports that ILS supplied them with. These reports were of the type described in section 4.4.3. They were based on qualified guesses and the experience of the people working at the ILS Department, together with the engineers consulted in the matter.

According to an interviewed ILS manager so far the customers have been satisfied with the level of verification but as maintainability becomes more and more important there might also be bigger demands on verifying the requirements more thoroughly. This will be a problem for Saab because as both representatives from I&V and ILS conclude: The maintainability analyses have been real eye openers on how poor the maintainability is in some cases.

In the case with the ECU in the Giraffe AMB 1 the customer was made aware of the poor maintainability of the ECU according to a Project manager. However it is reasonable to believe that the customer may have thought that it was alright if the ECU had a high MTTR, but if the "real" MTTR value for the ECU would had been incorporated into the MTTR for the entire system this would have had the effect that the value would have been higher than what was agreed upon in the purchasing agreement. Would the customer have been satisfied with that?

5.4.RQ2 Results - Review and Verification of Maintainability

RQ2: How are maintainability requirements and their fulfilment reviewed during the on-going development and verified in the finished system?

More time should be given to the review meetings and efforts should be taken to avoid unevenly distributed meeting time for different units and issues depending on the champions of particular causes or those who voice their opinions the loudest. The reviews of maintainability should be discussed from a more detailed level where the repair time MTTR is broken down into practical tasks. What this structure could look like is presented in the results of RQ3. As with all organisations, changes and where to direct the focus needs to be supported by the management. Without their encouragement and attention issues like maintainability can easily be bypassed since it is not as easily measured as fulfilment of a function requirement. Maintainability needs to be raised to a higher level and motivated better than it is today.

Reviews could also greatly benefit from using prototypes and other visualisation tools to aid the engineers. Using just a simple 3D-model on a computer or a paper printed model without proper actions taken to visualise aspects of the design to determine the ability to maintain and service a unit and components is insufficient and causes unnecessary and costly iterations and redesigning. Not having tools that support the reviewers and designers means that the problems are only pushed forward to a later and more expensive phase in the development. A simple solution suggestion to aid the current working process is presented in Figure 5-2 and in Figure 5-3. The authors have used the ECU case together with the air ducts and added in a supporting wall and floor (representing the cabin) and a manikin together with the unit. The method is an alternative or a complement to using prototypes since it is a very cost-effective way of visually presenting an object during a review. The model should of course be used together with a checklist for the different subtasks there are when repairing, replacing and servicing different components. A suggestion for this could be the task sequence presented in Figure 5-4 in chapter 5.6.1 in research question three.

Finally the creation of subsystem verification of maintainability is desirable to ensure that maintainability not only verified on the top system level. By verifying the maintainability prerequisites that are put on individual units problems can be discovered before the development of the entire system is complete.

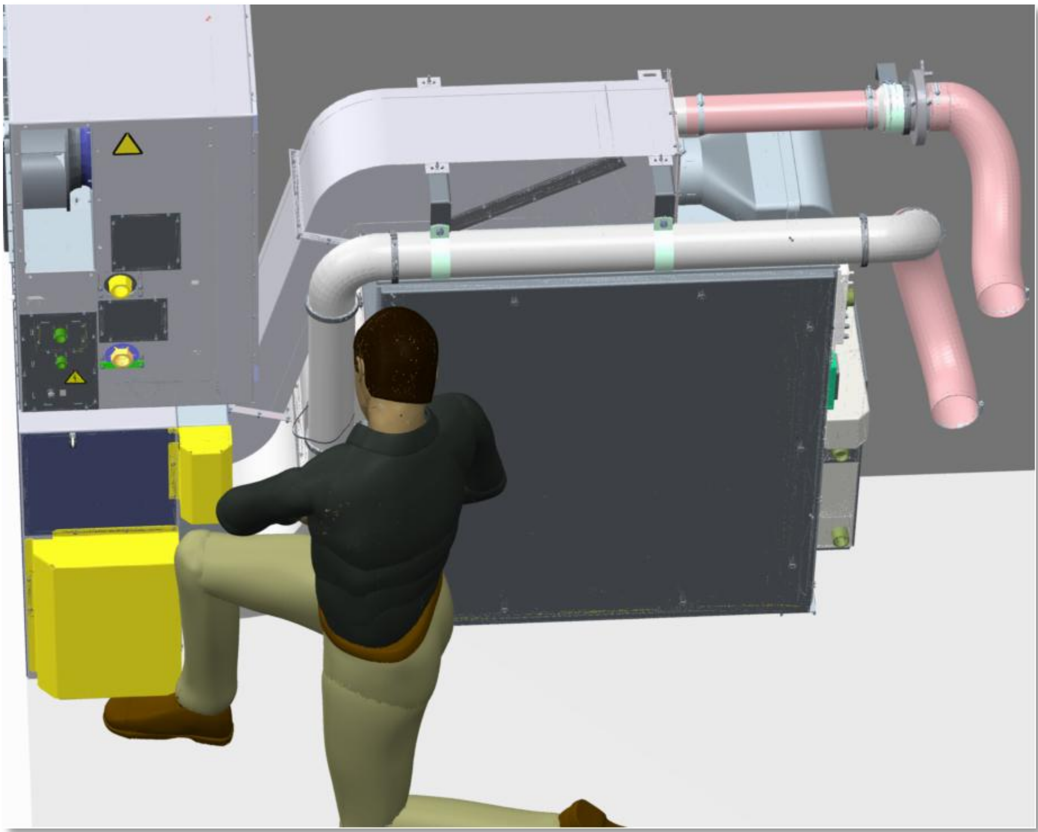

Figure 5-2 A CAD-image of the ECU and the connecting air ducts together with a manikin

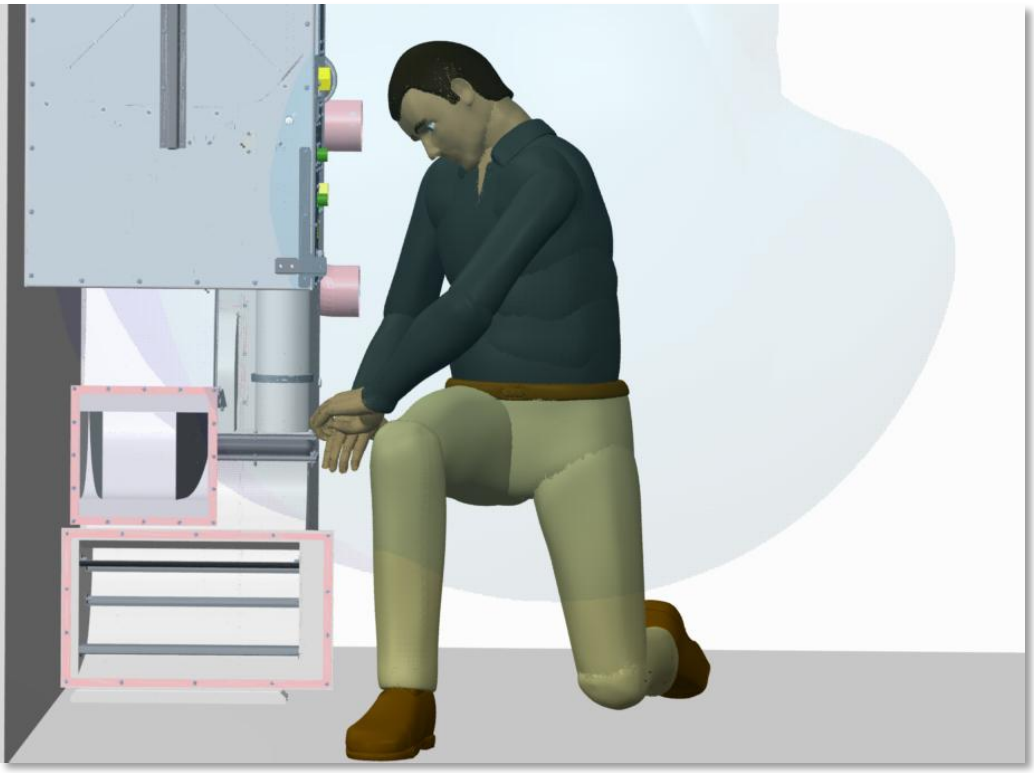

Figure 5-3 A CAD-image of the manikin and his limited reach

Using further visualisation tools like prototypes and mock-ups could also improve the development work to create a more realistic view of the product. These can be everything from very simple cardboard mock-ups to full-scale models. The benefits from a maintainability perspective are that the reviews, both formal and informal, will have an additional dimension to evaluate the ability to maintain and service the product. One of the problems today is that each unit is treated separately while the problems are usually the relationship between two or more. Since there is very little space to work with when designing a system like the Giraffe AMB the units are dependent on each other when they need to be serviced or repaired. The collaboration between the units therefore need more attention during both the designing and the reviews to create a good product.

The status of the maintainability is perceived as poor by the master thesis authors. Few engineers seem to be aware of how it should affect their work and is a consequence of the lack of support by the management and the methods used. Raising the issue more often and discussing how the system is used, maintained and serviced, as well as by whom, during its life cycle could strengthen the company brand and product reputation. However, for this to happen the employees need to know that it is an important and prioritised issue which only management can enforce.

Regarding the ECU case the unit was lifted in from another project in development without having gone through verification checks. What initially was thought to be a small adaption project to the Giraffe AMB became an almost six times more time consuming task than planned for and caused both extra cost and delay. The group of designers assigned to the unit had not been informed of the problems the unit had in the previous project and the miscommunication and verification checks could be seen as a source of the failure. Enforcing higher demands on reviewing the units and components that are reused could be a way to avoid future unplanned tasks.

As presented in theory on a previous case study performed at a car manufacturing company it was discovered that requirements were fulfilled differently depending on what verification method had been assign. At the company the requirements are not presented together with their verification method or why the requirement is set to begin with. They are kept in separate documents. If the choice of verification method affected the engineers at the car manufacturing company to make different choices depending on their input, it is possible that the engineers at the company do as well. To improve the design process a new way of presenting maintainability requirements is suggested by the thesis authors. The suggestion provides an overview of a breakdown of the maintainability requirement MTTR into subtasks together with a stakeholder for each subtask of the requirement, a verification method and how the subtasks will be achieved. The full suggestion is described more in detail in research question three.

Formalising the reviews, what they have to contain and result in could be a way to increase the quality and avoid costly iterations late in the product development. Also, motivate why the reviews are necessary and the negative effects late problems will mean for the project teams. The technical reviews also need to be improved. The checklists used today have the options of either yes, no or N/A for different features. In the case of the maintainability the feature is “Service and maintenance” as shown in Figure 4-3 in empirical findings. Just checking a box with a yes, no or N/A with no further comment is not a sufficient way to evaluate a unit. A short time solution could be to use the improvement suggestion presented in chapter 5.6.1 to analyse the design from the tasks required to repair a unit. For a more long term improvement efforts should be put in improving the TRW checklist or replace it with a better and more detailed reviewing method.

The Mechanics and Environment Department should also try to do *internal subsystem verifications* on their designs for faster and more flexible product development. This would increase the responsibility of the department to set up their own verification methods suitable for the prerequisites broken down from the requirements. In the results presented in RQ3 and Appendix D the authors have integrated this theory in a solution suggestion for the maintainability requirement (MTTR). The idea is to have the unit's maintainability prerequisite broken down to the subtasks it will take to restore it to a functioning mode again, the actual sequential repair steps. This method will help the design engineer to think of how the product should be serviced and maintained.

5.5.RQ3 Analysis - Tools and Methods to Support Maintainability

RQ3: How can existing tools and methods integrate maintainability better and are there any new that could be implemented?

In this chapter the tools and methods that further support maintainability at the company and that are not covered by the two previous chapters will be analysed.

5.5.1. The FMEA Method

General - FMEA

The current way of executing FMEAs has some interesting aspects to discuss. The analysis are handled and coordinated by the ILS Department and appropriate system or subsystem designers are involved at request from ILS. First of all, according to theory, a FMEA is best performed by a cross-functional team with representatives from different departments within the organisation such as production, design, marketing, service etc. In the company's case the two disciplines that take part of the FMEA corresponds to theory's service and design. From a maintainability point of view one can agree that these are the two departments that are vital to include. Though production has experience of assembling previous designs and could offer additional input. The way the FMEA is used at the company, what is interesting is what effects a failure has on the radar function, not what maintenance operations have to be performed to restore the failed component or system to a working condition after a failure has occurred. This might be one explanation to why production is not part of the FMEA team. However, this is possibly a weakness since one of the main reasons for conducting the FMEA in the first place is to improve the maintainability, therefore *what* maintenance that has to be performed after a failure, is a justified topic. If not considered in the FMEA it should be considered somewhere else. During recent year there has been a shift in reasons way FMEAs are conducted. Previously they were conducted to meet a customer requirement, but this has changed a bit and they are beginning to be used also for the development work itself. An important change has been that the analyses are conducted during the development work, instead of after like previously done.

The second aspect of Saab's way of executing FMEA is that theory states that a method should ideally be performed by the people who will later utilise it in their work in order for them to fully grasp the importance and meaning of the contents. If the FMEA is done only at a system level, by system engineers and ILS representatives, then the subsystem engineers who will design the components at the subsystem level might not be able to incorporate the results of the FMEA.

It is also important that the designers who are involved in the FMEA embrace its results and use it in their work. If this is not achieved then there is a great risk that the possibilities of improvements are lost. In comparison to the company, the car manufacturing company mentioned in the theory requires their engineers to be one of the key persons involved in the FMEA, thus making sure that they get the full advantage of the method.[36] This way of performing the FMEA also ensures that engineers working with a component have taken part of the FMEA. Good to remember is that tools and methods are used not just for the end result but also as important activities for a team to communicate and discuss system or product characteristics.

The ECU - FMEA

In the case of the ECU the FMEA method was performed, however not until after the development work was completed which gave the effect that the potential benefits from it was not used in the actual subsystem design work. The failure to do so might have been one of the reasons that the removal of the air ducts was not given enough attention. The FMEA that was finally made listed several components in the ECU as having a critical influence on the radar function, the fan being the component with the highest failrate. The design that was chosen did not make the fan, or hardly any of the other critical components, possible to replace without removing the ECU. The fact that the ECU had to be removed entirely should have been an indicator that the design had its faults and that the maintainability aspects of the removal of the ECU should have been regarded. Instead, a design of the connecting air ducts that made the removal of the air ducts very difficult was allowed to pass through the development phase.

If FMEAs would have been carried out in the way that theory dictates during the development of the ECU the removal of the air ducts would most likely have been addressed more thoroughly because of reasons described above. What more that can be learnt from the ECU-case and that has been mentioned in the previous chapter is that it could be a good idea to also incorporate the aspect of restoring the failed component to a working condition in the FMEA analysis because there seem to be a gap of information regarding how this is handled. Currently the parts that need replacement when a failure has occurred are defined as *replacement objects.* Depending on the detail depth chosen for the *replacement objects,* different numbers of components are included. Also, via the FMEA analysis the critical components are located, but the actual procedure of replacing them and what other components that affect this operation is not reviewed.

5.5.2. Design Guidelines for Engineers

It is the thesis authors' view that a different approach to the current design guidelines would benefit the company. The guidelines[37] that exist on maintainability issues are as described in the empirical

[36] Senior University Lecturer & Researcher. interviewed by: Ericson, J. & Andersson, E. (26th February 2013)
[37] Document number: 1020-FCK11540

chapter 4.5.1 very scarce and not much aid for the design engineer. As mentioned in the empirical findings chapter 4.5.1 this view is also shared by many departments at the company such as system designers, ILS representatives and system verification engineers. The guidelines are not referenced in any of the requirement or design specifications viewed in this case study and they are general documents that can be found in a large collection of other aids to utilise. If they are formally required to be used they should include the following guidelines on how to design for maintainability.

5.5.3. A3 - Design Specifications

The introduction of the A3 design specification has been a real improvement in the way maintainability is brought into the focus of the engineer according to experts from several areas, however it can still be improved. The current layout can be updated to strengthen the focus on maintainability aspects. The specification briefly summarises related documents on general issues that a designer needs to consider and references these documents through their document numbers in IFS. However, the points dedicated to maintainability do not link any other external documents or guidelines to help the designers to improve in this area. Therefore the specification does not provide the amount of support that would have been possible if maintainability would have been given more room.

It is important that the engineer understands what maintainability is and how to approach it because just bringing maintainability into the requirement specification and declaring it important does not automatically mean that it is taken into consideration and fulfilled. Results from a case study of a major Swedish car manufacturer mentioned in theory showed that those requirements that are not championed by an individual or a requirement specialist do not get enough attention and risks being suppressed and unfulfilled (Almefelt, et al., 2006). What this tells us is that highlighting the maintainability for the engineer is important but may alone not be enough. It is also important that someone, in this case probably the ILS Department, supports the engineer in these issues and makes sure that he or she has the information and tools needed to fulfil the maintainability requirements in a satisfying way. This is also confirmed by a system expert who calls for earlier and more continuous involvement of the ILS department in development projects. Improvement suggestions for the A3 – design specification is presented in the RQ3 -results chapter below.

5.6. RQ3 Results - Tools and Methods to Support Maintainability

RQ3: How can existing tools and methods integrate maintainability better and are there any new that could be implemented?

This chapter presents the results of third research questions, including both improvements to existing tools and methods and the addition of some new.

5.6.1. A New MTTR Methodology

As described in the theory, and shown in Figure 2-4 as well as further elaborated in Figure 5-4 below, it is only the shaded blocks (access, diagnosis, replace, check and align) of the MTTR that can be effected by the design. These blocks can be broken down into more comprehensible and realistic guidelines for how to approach a design task. This kind of visualisation of what a MTTR value really consists of could bring the designer closer to the user's perspective and trigger further thoughts on more specific and practical design solutions. The mean time to repair is the total time from unit breakdown until it has been repaired and functions properly again. Depending on the fault and unit the fault could be fixed either after the phases' replacement, check or align. As mentioned in the empirical findings the most difficult block to estimate is diagnosis.

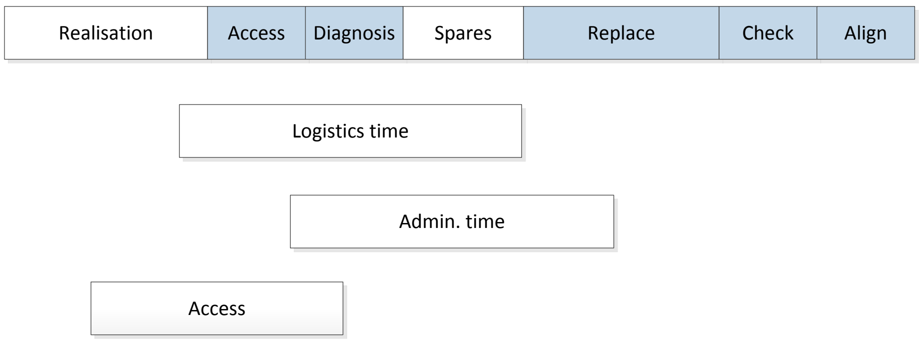

Figure 5-4 Elements of down time and repair time

The MTTR value for the entire ECU can be broken down in accordance with the methodology presented above and in theory combined with the company's definition of MTTR:

Access	Time required for the operations necessary to be able to access the faulty component. This may include removing the front panels of the ECU to reach components and to be able to connect test equipment.
Diagnosis	Time required for localisation of the failure source in the ECU.
Replace	Time for replacement of the faulty parts. In many cases this requires the entire ECU to be removed from the equipment room as described in empirical findings. This operation includes the removal of parts of the air ducts and disconnection of the ECU from the liquid cooling system. Also included is eventual remounting of the ECU and reconnecting it in the equipment room.
Check	Time for verifying that the failure has been resolved. Depending on the abilities to determine this the time might include time for necessary start-up of other systems.
Align	Eventual time required for adjustment of the ECU after component replacement to bring it into its former state.

The definition of MTTR that the company currently employs incorporates all of the aspects above, from access to align; they are however not handled as separate units in the requirement specification but as one value; MTTR. The break down brings the designer closer to the user's reality and it is easier to visualise the difficulties a particular design might present.

In the requirement specification the MTTR value that was stated for the ECU was 50 minutes. If this requirement would be divided according to the method used above the result could become something as seen in Table 5-2 below (note: the values set for the different topics are just an example of how the requirement value could be divided into different topics and is based on the thesis authors' own judgement and experience of the case):

Table 5-2 The MTTR of the ECU broken down on its subtasks

MTTR	**50 min**
▪ **Access**	5 min
▪ **Diagnosis**	10 min
▪ **Replace**	30 min
▪ **Check**	5 min
▪ **Align**	0 min

By dividing the MTTR value into these categories it can become more obvious for the engineer which different parts of the MTTR time that he or she can affect and which other parts that are governed by surrounding aspects. The ability to highlight the part of the MTTR value that can be affected by the engineer has been voiced as important by ILS and design representatives alike.

Another aspect that needs to be taken into account is the increased aid the method provides for estimating the MTTR requirement on underlying components. In the ECU case the air ducts would qualify as such components. As specified above the eventual removal of the air ducts would be included in the "replace"-phase. This knowledge, combined with the knowledge that the repair of many components in the ECU requires the removal of the air ducts, should give sufficient background information for an estimation of a reasonable MTTR time for the air ducts. The engineer should be able to realise that the removal time for the air ducts has to be significantly lower than the time for the "replace"-phase if the MTTR value for the ECU is going to be met.

In the ECU-case there has been no indication that the removal of the air ducts would be a big issue for the MTTR-value of the ECU and the only requirements that were stated for the air ducts were that they should be easily accessible for mounting and dismounting, a requirement that left much room for interpretation by the engineer. The dependency of units and connectors could be improved and reviews should take this more heavily in consideration.

5.6.2. A New Way of Handling MTTR Requirements

Implementing a new way of presenting the requirements together with their verification method in one document could improve the design work. Developing this idea further with examples from theory and case studies has also added further suggestions for additional columns, as presented in Table 5-3 and further developed with the MTTR methodology discussed in the previous chapter, visualised in Table 5-2. These two methods are combined in Table 5-4.

Table 5-3 A tailored table row for requirement management

Requirement	Main Stakeholder	Subsystem Verification	Design Decision

To further explain, the data presented in Table 5-4 is taken from Table 5-1 (page 50), the ECU's requirements and parameters. By gathering all information regarding the requirements and the prerequisites for a certain design in one document the designers get a more complete picture of what should be done, how it will be verified, who will be responsible for it and also how it will be practically realised. Table 5-4 is created by the authors of this master thesis and is suitable for working with maintainability requirements (constraints). For function requirements an additional column could be used for *justification* of setting a requirement, i.e. *why* the requirement is necessary and needs to be fulfilled. From the system to subsystem level in the company there is a loss of understanding and intent in what different requirements actually mean and why they are created and the justification column could help to prevent this. However, since functional requirements are outside the scope of the thesis this will not be further discussed.

The suggestion presented in Table 5-4 is also brought into a maintainability design specification created by the thesis authors to be used continuously through the development work. The worksheet can also be a useful tool to bring up during reviews to discuss the design solutions for fulfilling the maintainability requirements. The complete solution is shown in Appendix D completed with an example for the ECU and in Appendix E as an empty template. The company has also received a larger template in A3-format with an attached guide to what the different table sections mean.

A significant part of the information that is included in the maintainability design specification comes from the ILS Department. As a consequence it is highly dependent on their involvement and commitment to supply the subsystem designer with the information that he or she needs to utilise the method. As mentioned in chapter 4.5.3 System Experts desires the ILS Department to be involved earlier and more consistently in the project. At the same time ILS Managers has expressed the desire to be given the opportunity and therefore the possibility that it can be performed in the future seems good. As with many other aspects of product development a restricting factor is the time and resources available. Hopefully the company's management realises the importance of maintainability and entrusts ILS Managers and subsystem designers with the necessary resources.

Table 5-4 The new and more detailed way to break down the MTTR requirement

Requirement		Main Stakeholder	Subsystem Verification	Design Decision
MTTR	**50 min**	Subsystem responsible (DSA)	Maintainability analysis	Break-down into subtasks
▪ **Access**	**5 min**	Mechanical	Mock-up	Number of screws, easy accessible measuring points, captive screws etc.
▪ **Diagnosis**	**10 min**	Electrical	Analysis	BIT, labelling, sight, hearing, touch etc.
▪ **Replace**	**30 min**	Mechanical	Mock-up	Accessibility, visibility, manageability, weight, snap features
▪ **Check**	**5 min**	Mechanical/Electrical	Analysis	BIT, sight, hearing, touch etc.
▪ **Align**	**0 min**	N/A	N/A	Should not be required

5.6.3. Improvements to the FMEA

FMEAs today at Saab are done for the customer's benefit more than for the product development team which makes it a less effective tool. FMEAs should be incorporated as a natural and important part of the product development process. It should be one of the important methods in the development work and not just something that is conducted to fulfil a customer demand. It should not be performed only after the development, like the case of Giraffe AMB and the ECU, but be established before the design work when it has the most influence on the outcome.

It is important to involve the engineers conducting the design work in the FMEA to ensure that they are given every chance to utilize the results of it in their work. Finally, in order for the company to ensure quality, reliability and maintainability methods like FMEA should be given more time and resources. Efforts should be taken to ensure that the right people are part of the FMEA team and that team members are replaced from time to time, ensuring a fresh perspective of problems and solutions. To strengthen the focus on maintainability in the FMEA it may be a good idea to include the Production Department because they may have experience of assembling similar products.

5.6.4. Recommended Additions to the Design Guidelines

The authors suggest the follow addition to the current design guidelines[38] to incorporate maintainability better in the product development process better.

- Screw sizes chosen - to prevent choosing screws with only the needed strength of the joint in mind, may result in unnecessarily small screws being used which may be difficult to unscrew.
- Number of different screw sizes – limit the number of different sizes since this affects the number of different tools needed when assembling and disassembling the products. Overall a decision should be taken on a system level which sizes that should be allowed to be used, giving the design engineer a number of preferred screws to choose from. Deviation from these guidelines should be taken in conjunction with the design responsible. Implementing this suggestion is also a natural step in the company's move towards using a small number of *Base Line Products* where components are designed to be used in many different product families. This makes common guidelines of designs even more important.
- Fundamental guidelines for Design for Assembly and Design for Manufacturing. Exactly which these guidelines should be is outside the scope of this thesis, but the thesis authors recommend Product Design for Manufacture and Assembly (Boothroyd, et al., 2010).

If they are not formally required but merely exist to support the design engineer a different approach should be utilised to integrate maintainability better in the design work. Each development project should contain specific references to the maintainability aspects that should be considered to create a uniform product. One suggestion is to have a master document that controls as many units' design as possible, e.g. all units included in the climatic system or all units in the equipment room, to avoid unnecessary differences caused by too little communication between the design engineers.

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[38] Document number: 1020-FCK11540

5.6.5. Maintainability Design Specification

The final result of this master thesis is the maintainability design specification sheet. Here we integrate our new MTTR methodology that we presented above together with some other aspects that affect the maintainability of a design. A visualisation of the different parts included in the maintainability design specification is provided in Appendix F which can also be used as a guide when looking at Appendix D and E. The aspects included on this worksheet are:

- A requirement management table with the column headings *requirement*, *stakeholder*, *subsystem verification* and finally *design decision*.
- The critical components of the design with their respective failrate (taken from the FMEA).
- The non-critical components and their failrate to indicate their level of importance.
- The prerequisites like screw type and size, tools etc. ideally these should be chosen at a higher system level to enable a uniform design for the entire system with a minimum amount of different fasteners.
- The maintainability measurements MTBF and MTBCF are included as well as a reminder of the different requirements that are underlying the design decision and to give a completeness to the design work.
- A preventive maintenance table to provide information on how often components need to be replaced; Yearly, monthly or daily. This aspect was included very late in the iteration process at the request of two separate interviewees. The information of how often components need to be replaced can affect their placement in a unit, with the more frequently changed components more accessible than the rest. Preventive maintenance is particularly important in products that have high uptime and reliability demands.

Furthermore, on the topic of the prerequisites of the maintainability design specification the following should be noted. Either the maintainability design specification should contain a reference to a master document that decides what fasteners and tools should be used or the information in that document should be copied in to the specification. The master document should be a controlling document that ensures consistency throughout the design work. If a master document on a higher level of design for a cluster of units, e.g. the equipment room, does not exist it could be a potential future improvement. If this is not possible the authors suggest that "the design guidelines" that are linked from the mechanical engineers' collection of documents are used. The design guidelines could be stricter on what fasteners that are allowed to be used and minimise the amount of variation in the designs as much as possible. This suggestion is in line with the company's wish to move towards fewer units that are compatible in several different systems. See chapter 5.5.2 for the thesis authors' suggestion for how the design guidelines could be updated to support this topic.

The maintainability design specification should be referenced from the existing A3-design specification under the prerequisites headline like shown in Figure 5-5 below. The A3-design specification is used today as a collaboration document that summarises the most important things regarding the design. Referencing the maintainability design specification from here ensures that it will not be forgotten and that maintainability is an important topic that should be given more attention.

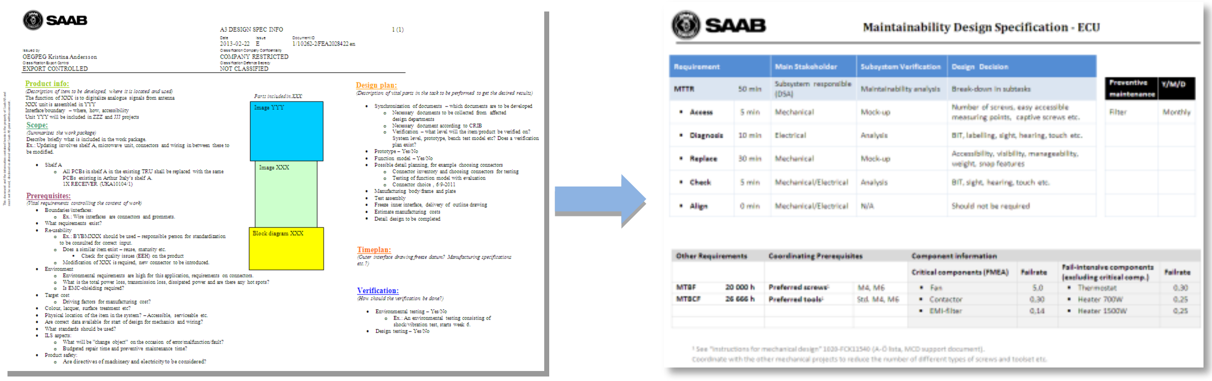

Figure 5-5 The linking relationship between the existing A3 design specification and the new maintainability design specification which can be found in appendices D (ECU) and E (Template). A reference to the maintainability design specification from the existing A3 design specification can improve the maintainability of the company's products.

6. DISCUSSION

The purpose of this master thesis has been to investigate how the system requirements on maintainability have been implemented and developed through the product development process. Spreading and increasing the knowledge of what maintainability is and what it practically means has also been a part of the work, and some improvement suggestions have been suggested and created. The authors started by investigating the formal process from the company's internal site and published documents. At the same time both formal and informal interviews of the company's work process was conducted. The interviews have been the most useful source of information since the documentation of the Giraffe AMB 1 has been difficult to trace and evaluate. A large amount of time was spent on mapping out the maintainability requirements and how they have been handled. This approach has meant that the authors have iterated in the information gathering process many times during the work.

The focus has been largely on what the Mechanics and Environment Department can do to increase the performance of their work in regards to maintainability. The reason for this focus is simple, maintainability depends largely on the actual physical design of the products and the subsystem in question is responsible for much of the design work at the company. However, the thesis was conducted for the Systems Design Department and their role and how they affect the maintainability of the products has not been forgotten during the thesis. The Systems Design Department has a vital role as they provide the subsystems with much of the initial inputs to the design work in form of the requirements for each subsystem.

The investigation of the Giraffe AMB and the ECU case required an extensive amount time and the focus was from the beginning set on academic literature and published case studies, rather than studying other industries. The gain of that focus is that a thorough and in-depth investigation has been conducted and several improvement suggestions have been made on a firm empirical study. However, further research in the area would greatly benefit from looking at how other organisations handle maintainability requirements, how they are set and fulfilled.

The master thesis was built around a specific unit chosen for its known low maintainability prerequisites. The work has greatly benefited from having something to investigate and to test the improvement suggestions on. It has supported the conclusions and brought issues to light that otherwise might not have been found.

The responsibility of managing the maintainability requirements could be seen as a grey area. The Systems Design Department might think that it is up to the subsystems s to make the necessary design decisions to live up to the entire system requirement. Meanwhile, the subsystems might think that they should be given more specific requirements for each unit or subsystem. The starting point in this thesis has been the notion that the key to improving the maintainability to a greater extent lays in giving the subsystems improved methods and tools to better interpret and work with maintainability. The main findings and related propositions from this master thesis are in summary:

- **Finding 1**

  MTTR requirements are not broken down on a subsystem level, instead they are transformed into prerequisites on the subsystem level with one value comprising of all the phases in a repair operation. As with many aspects of maintainability the understanding of how it should be handled differs from individual designers. Some might have deep knowledge of how a particular unit or component is serviced and maintained whilst others may not have that same understanding.

- **Proposition 1**

  A new MTTR methodology which divides the value into five main tasks: Access, Diagnose, Replace, Check, Align. By specifying the time needed for the different subtasks the aim is to give the designer a greater understanding of the requirement and what underlying aspects affect it. The proposition fits well into the company's current processes since the total sum of the MTTR value for the different subtasks will be the same as the MTTR value currently used. It will merely act as an aid for the design engineer without requiring system requirements to be formulated differently than how they currently are. Potential benefits of implementing this proposition is that it becomes more obvious for the engineer what different parts of the MTTR time he or she can affect and what other parts are governed by surrounding aspects.

- **Finding 2**

  Maintainability is only verified on a system level and then often with predictions, not maintainability analyses. During reviews it is poorly visualised with simple 3D-models shown out of context. The result of this is that maintainability problems risk going undetected throughout the entire development process without being discovered until the customer complains when using the products.

- **Proposition 2**

  With subsystem verification the aim is to be able to verify maintainability prerequisites on a subsystem level. The potential benefits are that maintainability problems are discovered whilst the development is still on-going. A subsystem verification facility also grants better possibilities to build mock-ups and prototypes to review maintainability during the development. The usage of manikins in 3D-models is another improvement that aims at increasing the visualisation of maintainability during reviews with the potential benefits of discovering maintainability issues early. Its implementation into the company's existing review processes should be able to be conducted without larger expense. The software needed is already available for the engineers and the additional costs is in the form of the time that is spent on using it, which should be able to be kept to a small amount according to the thesis authors' own experience. Setting up subsystem verification will be significantly more expensive, but is necessary if maintainability prerequisites are to be verified in a proper manner. The company has begun to plan for this but still lacks proper funding.

- **Finding 3**
  FMEA was executed after the product had been developed and then only to evaluate the result of the work and to be able to show the customer that the analysis had been conducted. The FMEA team was comprised of people mainly from the ILS Department.

- **Proposition 3**
  Conduct the FMEA in the initial phase of development with the aim of being able to utilise the results of it in the development work. Potential benefits are better products were the critical degree of certain components have been taken into consideration during the development together with the effects of component failure in terms of what repair tasks are needed.

- **Finding 4**
  The designers lack a supporting method concentrated on maintainability aspects and how these should be handled during development.

- **Proposition 4**
  The proposed *maintainability design specification* is a practical method with a human-centred approach to maintain and service units. It aims at bringing the aspects of maintainability closer to the designer in a concrete and applicable manner and is a method for the actual subsystem designer to use rather than the management. Potential benefits is that the lacking knowledge transfer between ILS, Systems Design and subsystems can be bridged by providing a better understanding of the maintainability aspects to the designers. This is important since the actual requirements are on such a high level as the entire enclosure and because these requirements then are continued on as design prerequisites for entire units. The result of this is that there is large room for individual interpretation by the design engineer. The design and exact content of the *maintainability design specification* is a result of an iterative process where subsystem designers, a system design responsible, ILS managers and system verification engineers have been given the possibility to provide their input and feedback. This process has increased the validity of the proposition and increased its chances of being successfully implemented into the company.

7. CONCLUSIONS

In this chapter three main areas will be presented. First, conclusions related to the answers of the research questions of the thesis. Secondly, a summary of the contributions the master thesis has resulted in. Finally, what possible areas for future research the thesis can serve as a starting point for.

Conclusions from the Research Questions

Based on the answers to the research questions that this master thesis was built around the following conclusions have been made.

- The company lacks well-defined company terms and jargon for maintainability/serviceability.
- There exists no subsystem verification of maintainability at the Mechanics and Environment Department and a system's maintainability is only verified on its system level, not the units included in the system.
- Maintainability issues are discovered very late in the product development process.
- The subsystem designers have few aids or guides to help them design from a maintainability perspective other than from their own judgement.
- The company has a very limited visualisation capability; the only tool that was used in the Giraffe AMB to evaluate the maintainability was simple CAD-models.
- The technical and hardware reviews do not support the maintainability aspects of a design.
- The reviews of the Giraffe AMB were too short on time and the maintainability suffered from it.
- The maintainability measures, MTTR, MTBF and MTBCF are not sufficiently explained and broken down to be practically useful to design after.

Summary of Contributions

The master thesis has in short contributed to the following points.

- A case-study of how maintainability is handled in an actual product development case at a Swedish defence company, revealing flaws with the current work method and giving suggestions for possible improvements.
- Suggestions of how maintainability aspects, mainly MTTR, can be handled in a better way during development. Both in the way requirements are formulated and broken down and how they are reviewed and verified.
- An example of how a MTTR methodology from theory can be adapted and implemented into a company's processes.

Areas of Interest for Future Research

To cover areas outside this master thesis's scope the authors have suggested a number of areas related to the topic that is of interest for future research. These identified areas can be used as a starting point for that research.

- Investigate how other companies, both within the Saab group and in the rest of the industry, work with maintainability. How their processes support it and how requirements of maintainability is handled.
- In-depth research of how subsystem verification can be used at the company during and after development to support maintainability.
- Research of how the company could improve its way of specifying maintainability requirements against subcontractors. The issue was mentioned by several interviewees during the thesis.

8. RECOMMENDATIONS TO THE COMPANY

- Management need to support maintainability by giving time and resources to the improvements suggested by the thesis authors as well as other methods that affects maintainability such as reviews, visualisation and communication between departments.

- Implement FMEA as a part of the development process to ensure that the affected people are part of the FMEA team.

- Visualise maintainability with manikins in the CAD-tool, mock-ups, and prototypes.
  - Useful during reviews
  - Useful during the everyday work and informal design discussions
  - Useful when communicating within and between departments

- Improve the quality of the reviews.
  - Rewrite the checklists and templates used for the reviews to better support and force difficult maintainability issues to be dealt with.
  - Provide sufficient time for the reviews and distribute it appropriately on the different discussion points.

- Setup subsystem verification for the Mechanics and Environment Department to enable verification of maintainability prerequisites.

- Increase the knowledge and awareness of maintainability by educating the employees of the subject.

- Define maintainability measurements, in particular MTTR, in more detail and make the requirements more understandable for the engineers working with them. As a suggestion, with the maintainability design specification created in this thesis, shown in appendix D,E and F.

9. REFERENCES

Almefelt, L., Berglund, F., Nilsson, P. & Malmqvist, J., 2006. Requirements management in practice: findings from an empirical study in the automotive industry. *Research in Engineering Design*, 17 3, pp. 113-134.

Blanchard, B. S., 1991. *System Engineering Management.* New York: John Wiley & Sons, Inc.

Blanchard, B. S. & Fabrycky, W. J., 2006. *Systems engineering and analysis.* 4th ed. New Jersey: Pearson Education Inc..

Blanchard, B. S., Verma, D. & Peterson, E. L., 1995. *Maintainability - A Key to Effective Serviceability and Maintenance Management.* s.l.:John Wiley & Sons.

Blischke, W. R. & Murthy, D. P., 2003. *Case Studies in Reliability and Maintenance.* Hoboken, New Jersey: John Wiley & Sons, Inc.

Boothroyd, G., Dewhurst , P. & Knight, W. A., 2010. *Product design for manufacture and assembly.* s.l.:CRC PressI Llc.

Cassell, C. & Symon, G., 2004. *Essential Guide to Qualitative Methods in Organizational Research.* s.l.:Sage Publications Limited.

Dhillon, B. S., 2006. *Maintainability, maintenance, and reliability for engineers.* s.l.:CRC.

Eppinger, S. D. & Ulrich, K. T., 2012. *Product design and development.* 5 ed. s.l.:McGraw-Hill.

Gillham, B., 2010. *Case Study Research Methods.* London: Continuum International Publishing.

Hull, E., Jackson, K. & Dick, J., 2011. *Requirements Engineering.* London: Springer.

James, J. V., 2006. *Integrated logistics support handbook.* 3rd ed. New York: McGraw-Hill.

McDermott, R. E., Mikulak, R. J. & Beauregard, M. R., 2009. *The Basics of FMEA.* 2nd ed. New York: Productivity Press.

Rubenowitz, S., 2004. *Organisationspsykologi och ledarskap.* Vol. 3 ed. Lund: Studentlitteratur AB.

saabgroup.com, 2010. *Saab Corporate Brochure: "With a Mission to Make People Safe".* [Online] Available at:
http://www.saabgroup.com/Global/Documents%20and%20Images/About%20Saab/Company%20Pr

ofile/SAAB_Corporate_Brochure.pdf
[Accessed 28 01 2013].

saabgroup.com, 2010. *Saab Image bank.* [Online]
Available at: http://www.saabgroup.com/en/About-Saab/Newsroom/Image-bank/
[Accessed 28 01 2013].

saabgroup.com, 2010. *Saab in brief.* [Online]
Available at: http://www.saabgroup.com/en/About-Saab/Company-profile/Saab-in-brief/
[Accessed 28 01 2013].

Smith, D. J., 2005. *Reliability, Maintainability and Risk.* 7th ed. Tonbridge, UK: Butterworth Heinemann.

Smith, D. J., 2011. *Reliability, Maintainability and Risk - Practical Methods for Engineers.* 8th ed. s.l.:Elsevier.

Stake, R. E., 1995. *The Art of Case Study Research.* 6 ed. s.l.:Sage Publications Limited.

Stevens, R., Jacksson, K., Brook, P. & Arnold, S., 1998. *Systems engineering - coping with complexity.* 1 ed. Hemel Hempstead: Prentice Hall Europe.

U.S. Department of Defense, 2005. *DoD Guide for Achieving Reliability, Availability, and Maintainability (RAM),* Washington, DC.: s.n.

10. APPENDICES

Appendix A – Requirement Specification for Enclosure

Excerpt from doc. No.: 2/1029-UAZ10170/25

"Requirement Specification for Enclosure in GIRAFFE AMB System UAZ10170/25 GAMB-1"

Reliability

The system shall achieve a minimum basic (logistic) reliability, i.e. mean-time between-failure, MTBF, of 500 hours.

NOTE: Including the IFF.

Maintainability

Rack mounted printed circuit boards shall be provided with mechanical keys.

Preventive Maintenance

Requirement: It shall be possible to read the run-time

a. For all Units which shall have maintenance in a defined time interval.
b. Without any tools.

Exception: Tools are needed to read the run-time for the TRU.

Requirement:
Preventive Maintenance shall be

a. < 8 hours per year. (Annual Maintenance)
b. < 3 hours per month. (Monthly Maintenance)
c. < 30 minutes per day, (Daily Maintenance) and < 5 minutes per activity

Preconditions: The following average usage profile applies: 150 hours per month = 1800 hours per year.

Corrective Maintenance

For the system the MTTR shall be less than 60 minutes.
The corrective maintenance time (MTTR) is the time necessary to restore the system into operational condition by replacing a unit, LRU or part LRP. The time needed to repair the faulty unit at workshop is not included. These active maintenance tasks do not consider the effects on elapsed maintenance time due to logistic problems or administrative procedures.

MTTR shall be calculated by using a time summing method similar to those contained in MIL-HDBK-472. The corrective maintenance task is performed at operational level and includes the following subtasks:

- Fault isolation
- Replacement
- Alignment and checkout

MTTR = sum(Lambda(i) * RP(i)) / sum(Lambda(i)) where

Lambda(i) = failrate for item i

RP(i) = repair time at operational level for item i

Appendix B - Interviews

Interviews at Saab Electronic Defence Systems

Title	Division	Date	Duration	Interview Type
ILS Manager, Systems Engineers, Systems Verification Engineer	DI, DG	2013-01-24	1 h	Unstructured
ILS Manager	DI	2013-01-29	1 h	Semi-structured
Systems Engineer	DG	2013-02-04	1 h	Unstructured
Design Engineer	PE	2013-02-04	0.5 h	Semi-structured
Design Engineer	PE	2013-02-11	0.5 h	Semi-structured
Systems Engineer	DG	2013-02-11	1 h	Semi-structured
Systems Verification Engineer	DG	2013-02-14	1.5 h	Semi-structured
Systems Engineer	DG	2013-02-19	1 h	Unstructured
ILS Manager	DI	2013-02-22	1 h	Semi-structured
Customer Educator	DI	2013-02-28	1 h	Semi-structured
Design Engineer	PE	2013-03-04	0.5 h	Semi-structured
Systems Engineer	DG	2013-02-25	1 h	Unstructured
Customer Educator	DI	2013-02-28	E-mail	Structured
Assembly Worker	NS	2013-03-11	0.5 h	Semi-structured
Project Planner	PL	2013-03-18	1 h	Unstructured
Systems Engineer	DG	2013-04-19	1 h	Semi-structured
Systems Verification Engineer	DG	2013-05-13	0.5 h	Semi-structured
Subsystem Designer	PE	2013-05-15	1 h	Semi-structured

Interviews with Experts

Title	Department	Date	Duration	Interview Type
Senior University Lecturer & Researcher	Product Development	2013-02-26	2 h	Semi-structured

Appendix C - Interview Questions

Design Engineers

- What do you work with?
- How do you work in a project?
  - What is your roll in a project?
  - How much are you able to affect other parts than the unit you are working with?
  - How much contact do you have with other departments?
- How does the process look when you get an assignment?
  - What information is provided? (physical aids, explanation of design specifications etc.)
  - What types of guidelines do you have to help you?
  - What type of evaluation of finished work is performed? According to what criteria?
- Have you ever used an A3-specification? Do they provide any help?
  - What information is missing?
- What problems are there with information on serviceability when designing components?
  - Access?
  - Time for assembly/disassembly?
- How is your work verified when you are done? Especially regarding the serviceability.
- Are the system requirements difficult to interpret? Are they organised in a way to support the designer?
- Should the design be more regulated from a system level? Is too much decided individually by the designer?

Systems Engineers

- What do you work with?
- What was your roll in the project Giraffe AMB?
- What was most focus put on? Precision, cost, usability, reliability etc.?
- What do you see as a problem with the serviceability in the equipment room?
  - How do you experience the serviceability in the equipment room? The placement of units?
- How were the requirements on serviceability broken down from a top level?
- How much do you control the different subsystems and trade-offs between the departments? How active are you in the subsystems?
- How do the information exchanges look between the subprojects and departments? Are they sufficient?
- What guidelines do the designer engineers get to be able to work with serviceability? Common sense? Education?
- What is the biggest problem with serviceability? The design engineers interpretation of the requirements, lack of education etc.?
- What kind of methods are there today that deals with serviceability?
- What should you bring with you to future projects?

Systems Verification Engineers

- What do you work with?
- What was your roll in the project Giraffe AMB?
- What kind of methods did you use when you verified the serviceability on the Giraffe AMB?
- When did you join in in the project Giraffe AMB?
- What can you do during a project?
- When a project is finished, is there any follow up do to improve future projects? Feedback?
- What do you see as a problem with the serviceability in the equipment room?
- How do you verify that a requirement like MTBCF is really fulfilled?
    - How is the reliability in these methods?
    - Under what phases in the project do you verify?
- Do you know anything that could help you in your work as a verifier? What do you miss?
- What should you bring with you to future projects?

ILS Managers

- What do you work with?
- How do you work in a project?
    - What is your roll in a project?
- What do you see as a problem with the serviceability in the equipment room?
    - How do you experience the serviceability in the equipment room? The placement of units?
- Does ILS use FMEAs?
    - Who uses these analyses?
- What information did you use of the MTTR and the MTBF during the development of the Giraffe AMB?
    - Where these never broken down to the design engineer as guidelines to work from?
- Is ILS responsible for the verification of MTTR etc.?

Senior University Lecturer & Researcher

- From the experience you have both from the car manufacturing industry and as a researcher, what are the main problems with serviceability requirements?
- How should serviceability requirements be formulated and set to be practically implemented?
- How can we help the company work better with their requirements from what we have told you?
- What other industries could be useful to look at?
- How are successful reviews conducted?
- What methods can be used to identify serviceability requirements?

Appendix D – Maintainability Design Specification - ECU

SAAB

Maintainability Design Specification - ECU

Requirement		Main Stakeholder	Subsystem Verification	Design Decision
MTTR	50 min	Subsystem responsible (DSA)	Maintainability analysis	Break-down in subtasks
▪ **Access**	5 min	Mechanical	Mock-up	Number of screws, easy accessible measuring points, captive screws etc.
▪ **Diagnosis**	10 min	Electrical	Analysis	BIT, labelling, sight, hearing, touch etc.
▪ **Replace**	30 min	Mechanical	Mock-up	Accessibility, visibility, manageability, weight, snap features
▪ **Check**	5 min	Mechanical/Electrical	Analysis	BIT, sight, hearing, touch etc.
▪ **Align**	0 min	Mechanical/Electrical	N/A	Should not be required

Preventive maintenance	Y/M/D
Filter	Monthly

Other Requirements		Coordinating Prerequisites		Component information			
				Critical components (FMEA)	Failrate	Fail-intensive components (excluding critical comp.)	Failrate
MTBF	20 000 h	**Preferred screws**[1]	M4, M6	▪ Fan	5,0	▪ Thermostat	0,30
MTBCF	26 666 h	**Preferred tools**[1]	Std. M4, M6	▪ Contactor	0,30	▪ Heater 700W	0,25
				▪ EMI-filter	0,14	▪ Heater 1500W	0,25

[1] See "instructions for mechanical design" 1020-FCK11540 (A-Ö lista, MCD support document).
Coordinate with the other mechanical projects to reduce the number of different types of screws and tools.

Appendix E – Maintainability Design Specification - Template

SAAB

Maintainability Design Specification - Template

Requirement		Main Stakeholder	Subsystem Verification	Design Decision
MTTR	x min			
▪ **Access**	x min			
▪ **Diagnosis**	x min			
▪ **Replace**	x min			
▪ **Check**	x min			
▪ **Align**	x min			

Preventive maintenance	Y/M/D
Component 1	
Component 2	
Component 3	
Component 4	
Component 5	

Other Requirements		Coordinating Prerequisites		Component information			
				Critical components (FMEA)	**Failrate**	**Fail-intensive components (Excluding critical components)**	**Failrate**
MTBF	x h	**Preferred screws**[1]		▪ Critical Component 1	x	▪ Component 1	x
MTBCF	x h	**Preferred tools**[1]		▪ Critical Component 2	x	▪ Component 2	x
				▪ Critical Component 3	x	▪ Component 3	x

[1] See "instructions for mechanical design" 1020-FCK11540 (A-Ö lista, MCD support document).
Coordinate with the other mechanical projects to reduce the number of different types of screws and tools.

Appendix F – A Guide to the Maintainability Design Specification with an Example from the ECU

Requirement Management: Each requirement is assigned a stakeholder that can affect the fulfilment the most. The requirement should also be assigned a method of verification to be able to test it. Finally the actual design decisions taken to fulfil the requirements are filled in continually as the work progresses.

The MTTR (an indirect requirement of the ECU): is broken down on its sub-operations to better help visualise the action of repairing an item.

Requirement		Main Stakeholder	Subsystem Verification	Design Decision
MTTR	50 min	Subsystem responsible (DSA)	Maintainability analysis	Break-down into subtasks
▪ **Access**	5 min	Mechanical	Mock-up	Number of screws, easy accessible measuring points, captive screws etc.
▪ **Diagnosis**	10 min	Electrical	Analysis	BIT, labelling, sight, hearing, touch etc.
▪ **Replace**	30 min	Mechanical	Mock-up	Accessibility, visibility, manageability, weight, snap features
▪ **Check**	5 min	Mechanical/Electrical	Analysis	BIT, sight, hearing, touch etc.
▪ **Align**	0 min	N/A	N/A	Should not be required

Preventive maintenance	Y/M/D
Filter	Monthly

Preventive maintenance: is done yearly, monthly or daily. This offers an indication of the components' placement in the unit depending on the frequency of its replacement.

Other Requirements	Prerequisites	
MTBF 20 000 h **MTBCF** 26 666 h		
	Preferred screws	M4, M6
	Preferred tools	Std. M4, M6

Component Information			
Critical components (FMEA)	Failrate	Fail-intensive components (Excluding critical comp.)	Failrate
Fan	5,00	Thermostat	0,30
Contactor	0,30	Heater 700W	0,25
EMI-filter	0,14	Heater 1500W	0,25

Other requirements: relevant to the unit's maintainability, i.e. MTBF and MTBCF.
The prerequisites: The preferred screws and tools used for the entire system to reduce the differences between units and to help the user.

Component information: The identified critical components are listed separately from the non-critical components. The components are listed according to their failrate to help the designer to better place these in the unit.