A model on how to use field data to improve product design: A case study
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**Abstract (in English)**  
To stay competitive, companies are forced to improve their products continuously. Field data is a source of information that shows the actual performance of products during operation, and that information can be used to clarify the items in need of improvements. This master thesis aims at identifying the set of field data that is required for dependability improvements and to develop a working procedure that enables increased utilization of the field data in order to make cost-effective design improvements. To achieve this, a 12-step model called the Design Improvement Cycle (DIC) was developed and tested in a single case study. The field data need was identified using a top-down method and was included as a part of the DIC.

Testing of the model showed that it was practicable and each step could be carried through, even though the last steps only could be tested hypothetically during discussions with concerned personnel. The model implied a working procedure that should be aimed at, according to personnel with competence within the subject. As the DIC appeared to be very flexible it should be possible to use within several areas. It was discovered that field data was not a sufficient source of information to support design improvements but it could be used to indicate which items that should be focused on during further investigations. The quality of the field data had a big impact on the analysis possibilities and to point out which data quality issues that had to be amended to make the data more useful, the data need for dependability improvements could be used.

**Key Words**  
Design improvements, Field data, Failure reports, Dependability, Case study, Cost-effectiveness

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Karolina Christoffersson
Definitions and abbreviations

**Availability**: “The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided” (IEC 60050-191-02-05:2002)

**Dependability**: “The collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance” (IEC 60050-191-02-03:2002)

**Design and development**: A “set of processes that transforms requirements into specified characteristics or into the specification of a product, process or system” (IEC 61160:2005, p. 7)

**Design review**: “A formal and independent examination of an existing or proposed design for the purpose of detection and remedy of deficiencies in the requirements and design which could affect such things as reliability performance, maintainability performance, maintenance support performance requirements, fitness for the purpose and the identification of potential improvements” (IEC 60050-191-17-13:2002)

**Down time**: “The time interval during which an item is in a down state” (IEC 60050-191-09-08:2002)

**Failure (an event)**: “The termination of the ability of an item to perform a required function”. (IEC 60050-191-04-01:2002)

**Failure cause**: “The circumstances during design, manufacture or use which have led to a failure”. (IEC 60050-191-04-17:2002)

**Failure intensity (instantaneous)**: “the limit, if this exists, of the ratio of the mean number of failures of a repaired item in a time interval \( (t, t + \Delta t) \), and the length of this interval, \( \Delta t \), when the length of the time interval tends to zero” (IEC 60050-191-12-04:2002)

**Failure mode**: “The predicted and observed results of a failure cause on a stated item in relation to the operating conditions at the time of the failure”. (EN 50126:1999, 3.13)

**Fault (a state)**: “The state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources”. (IEC 60050-191-05-01:2002)

**Field data**: “Observed data obtained during field operation” (IEC 60050-191-14-17:2002) In this report the field data will be connected to dependability.

**FMEA** (Failure Modes and Effect Analysis): A tool or procedure with which systems can be analyzed in order to find possible failure modes and ascertaining their cause and effect. The severity of failure modes can be identified with this procedure, hence providing input to improvement actions. Failure Modes, Effects and Criticality Analysis (FMECA) is an extended FMEA which adds a severity ranking which makes it easier to prioritize among the identified issues. (IEC 60812:2006)
**FRACAS** (Failure Reporting, Analysis and Corrective Action System) is a procedure that can be used for tracing problems or errors, analyzing them, identifying the root cause and correcting them. It should be seen as a closed-loop system from identifying the problems to taking care of them. Through utilizing the FRACAS process, faults related to e.g. design and workmanship can be traced. (IEC 60300–3–1:2003)

**FTA** (Fault Tree Analysis): The fault tree is a graphical description of the events that possibly lead to a defined top event. Its top-down approach aims at finding the cause or combined causes of the top event (IEC 61025:2007).

**HAZOP** (Hazard and Operability studies): The aim with HAZOP is to identify possible deficiencies and determining their cause and effect. According to IEC 61882:2001, HAZOP should be carried out by a team and during the examination the system is divided into parts which are searched for unwanted deviations from intended functions with help from guide words. (IEC 61882:2001)

**Maintainability** (performance): “The ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.” (IEC 60050-191-02-07:2002)

**Maintenance strategy**: “Management method used in order to achieve the maintenance objectives” (EN 13306:2001, p. 9)

**Maintenance support** (performance): “The ability of a maintenance organization, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy. (IEC 60050-191-02-08:2002)

**Pareto analysis**: The basic idea with the Pareto principle is that a small amount of causes (about 20%) affect a big amount of the outcomes (ca 80%). By using this approach it is easy to focus on the most important aspects, i.e. the ones that have the biggest effect. (IEC 60300–3–1:2003).

**Product design**: An activity where an object is created with help from available information. In the early, conceptual, design phase, requirements are converted into functional and subsequent physical descriptions. During the detailed design phase, physical components and their specified features are designed. (Kusiak, 1999)

**Reliability** (performance): “The ability of an item to perform a required function under given conditions for a given time interval” (IEC 60050-191-02-06:2002)

**Reliability Block Diagram** (RBD): A dependability analysis method which gives a graphical presentation of the reliability performance of a system. In the diagram, the connection between components in a functional system is shown, based on what effect they have on each other. (IEC 61078:2006)
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1 Introduction

This section gives the background on the need to improve product designs by using field data analysis. It includes discussions about its importance and associated problems. The problem formulation and purpose outline the aim of the project. Further, the relevance is discussed along with delimitations and a general timeframe for the project.

1.1 Background

Due to the competitive marketplace that signifies the business world today, Hallquist & Schick (2004) imply that it is essential for companies to manufacture products with high quality and to consistently work with discovering, tracking and correcting problems throughout the product life cycle. Continuous improvements of product quality is essential in order to be a strong actor on the global market, according to Shakeri et al. (1999), who further enhance that design and manufacturing processes need to be improved to decrease cost and delivery times. In addition, Sandtorv et al. (2005) and Brennan & Stracener (1992) indicate that the use of cost-effective design has become increasingly important.

Marcorin & Abakerli (2006) explain that manufacturers need to know about the performance of their products to be able to improve them. Data from the field is brought up by Cotroneo (2006) as a good source for understanding the reasons to failures and he upholds that it enables improvements in quality of products that will be delivered later on. In the International Standard, IEC 60300-3-2:2004, it is stated that the goal with data gathering is to improve products and processes with help from suitable analysis. It is meant to help in understanding the costs related to the products and thereby enable increased profit. Moreover, when data about dependability of delivered products is collected, the design of coming products can be improved.

According to Blanks (1998) failure data is a necessary input for the designers when making new designs aimed towards lower Life Cycle Cost (LCC) and higher reliability. Additionally, Balaban & Kowalski (1984) state that field data is the true measure of what has been produced and mean that the real reliability performance and trends are essential feedback for designers and analysts. Reporting of failures has many advantages, according to Holmberg & Lönnqvist (1997), e.g. initiation of improvements in product design on either present or future products, evaluation of requirement fulfillment, support in predictions and discovery of not foreseen failure modes and hazards.

Coit & Dey (1999) also acknowledge the importance of field data and explain that many companies and industries have started field-data collection programs. They uphold that field data outclass testing since it is impossible to simulate all conditions from the operative environment in a testing area. However, Loll (2006) means that few companies actually make use of or analyze the field data in a good way, even though the usage of field data often is the only way of estimating performance correctly.

1.2 Problem discussion

Irrespective of its importance, Jauw & Vassiliou (2000) stress that many organizations have problems gaining necessary field data, since collection of data about failures and performances from the field often is disregarded and the data tends to be inaccurate, incomplete or have shortcomings in uniformity. Moreover the data may be stored in many different locations. They state that the collection of this data is one of the biggest challenges...
Introduction

When analyzing reliability and product quality, Sattler & Schallehn (2001) mention that data analysis is dependent on the quality of the input data which often needs to be preprocessed. In many cases, much effort has to be put on preparing and processing data and it is estimated that 50-70 percent of the time for data analysis is put on this, which leaves little room for actual analysis, Sattler & Schallehn (2001). When analyzing failure data, Johansson (1997) and Moubray (1997) uphold that it may be problematic to define the causes of failures, and emphasize that, often, the repair is described, but not the fault, failure mode, failure effect or how the failure was discovered. Also the external factors (e.g. mishandling or poor maintenance, Hudoklin & Rozman, 1996) and failure symptoms are frequently left out.

Additionally, Cotroneo (2006) means that it is quite common that the owners of the data are unwilling to make it available for others since it can be seen as strategically suitable to keep the data to oneself. Another problem, enhanced by Smith (2005), is that failure reporting and analysis is very costly since it takes much time, and therefore the follow-up must be motivated with the possibility of making savings that exceed the cost of analysis. Al-Najjar (1999) explains that cost-effective improvements may cause extra expenses in the beginning but in time the change will be more economically feasible than the original approach.

1.3 Presentation of problem
Due to its acknowledged advantages it is beneficial for manufacturers to use field data in an effective way since it gives information about how the products operate in their real environment and indicate where improvements are needed. There is not always a clear view on which data that are necessary or a distinguished way of extracting and utilizing that data though, and that is a quite common shortcoming in companies. The engineers who are intended to modify the design of future products need proper information to be able to evaluate the necessity of change. The information can be used to support design reviews and initiate design improvements which, in turn, lead to better, more cost-effective products. The procedure thereby supports continuous improvements, which is a requirement for successful companies.

One way of evaluating the performance of products is by measuring dependability, which is a wide measure that includes availability performance and its constituents’ reliability performance, maintainability performance and maintenance support performance, IEC 60050-191-02-03:2002 (see Figure 1:1). In this report, new design that improves dependability in order to make the products more cost-effective is the primary focus.

![Figure 1:1 Dependability (based on figure 191-2 - Performance concepts, IEC 60050-191:2002, p. 100)](image-url)
1.4 Problem formulation
Based on the above information, the following research question has been formulated, which intends to be answered in the report;

- Which field data are needed and how should these be assured and utilized in order to support cost-effective design improvements of existing and new product generations, with respect to dependability?

1.5 Purpose
The purpose of this study is to identify the set of field data that is required for dependability improvements and to develop a working procedure that enables increased utilization of the field data in the design process. This will generate more cost-effective and dependable products when modifying or designing existing and new product generations. It will be made possible through the creation and testing of a model that gives suggestions on which data that are necessary and how these should be used.

1.6 Relevance
The scientific coverage within this area is quite weak. Though, several researchers have given suggestions on which data should be reported in connection to maintenance, enabling evaluations of performance in the field (see e.g. Abbey, 2008; Balaban & Kowalski, 1984; Blanks, 1998; Ireson et al, 1996 and Smith, 2001). Regarding the process of gathering and utilizing the field data the research is more insufficient. However, Cui & Khan (2008) and Ortiz et al (2008) have given some recommendations related to the medical and airplane industry, respectively. On the same subject, Jauw & Vassiliou (2000) have described the design of a system that handles field data. Analytical tools have been found but they are mainly focused on mathematical/statistical models on how to calculate reliability etc. (see e.g. Balaban & Kowalski, 1984; Coit & Dey, 1999; Jung & Bai, 2007 and Marcorin & Abackerli, 2006) and not the actual way of assuring and utilizing the data for e.g. design improvements. Furthermore, there seems to be a lack of connection between field data and design improvements since hardly any relevant references have been found within this subject.

As mentioned above, field data is regarded as a good source of information but there are many problems related to the collection and analysis of it. A study on this specific area can function as a support for companies in their aim for constant product improvement and is therefore useful and has high practical relevance.

1.7 Delimitations
One single case study will endorse this thesis with empirical facts. Regarding dependability, mainly availability performance, including reliability performance and maintainability performance will be taken into consideration. The reason for excluding the maintenance support performance is that is more connected to the maintenance system while the others are connected to the product and the design. Not all products delivered by the company in the case study will be regarded. Instead a few of the ones used on the Swedish market have been in focus. The field data that is regarded comes from service workshops and spans over the warranty time of the products. Data from condition monitoring tools will not be included in the evaluation.
It will not be possible to test the entire model, since the procedure of developing a new design is time-consuming. Therefore, actual testing will only be conducted up until a certain point while the subsequent parts will be tested through discussions with personnel at the case company. The cost-effectiveness will be discussed but detailed data about the costs will not be available, making it impossible to use defined figures in the discussions.

1.8 Timeframe

The timeframe, presented in Figure 1:2, places the writing of different parts of the report into a perspective.

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Figure 1:2 – Timeframe
2 Research methodology

In this chapter, the research methodology for the project is accounted for. The general approach is described, as well as the data gathering and its methods. Validity and reliability is also discussed along with the possibility of making generalizations.

2.1 Scientific Approach

Thurén (2004) describe three different methods for drawing conclusions. They are; Induction, deduction and hypothetic-deduction. When using induction, empirical facts are used for constructing theories. Patel & Davidsson (2003) describe it as an exploring method which starts with empirical examinations in specific cases after which a theory is formed. They mean that these theories are hard to generalize. With the deductive method, Thurén (2004) explains that conclusions are based on logic reasoning. Patel & Davidsson (2003) clarify that, when using deduction, the researcher draws conclusions from existing theories and assume that they are valid in real life. Deduction enables a more objective way of working compared to induction, according to Patel & Davidsson (2003), but a problem may be that the existing theories restrain the researcher. In the third method, hypothetic-deductive, which is an elaboration of deduction, conclusions are drawn from theories, after which the conclusions are tested in reality to see if they are true.

In this project, the approach will be mainly hypothetic-deductive since a large number of theories concerning the subject will be studied initially and support the creation of a new model, which signifies a deductive way of working. Thereafter, the model will be tested at the case company to evaluate whether it is useable or not, using the hypothetic-deductive method. Deduction will enable approaching the problem in a more objective manner than if induction would have been used. However, Patel & Davidsson (2003) mean that the theories may cause the researcher to be restrained which will make it hard to come up with new ideas. Therefore, there will be a need to have an open mind and possibly modify parts of the new model with help from experts at the university and the case company.

2.2 Research Design

This project will be conducted through a single case study. A case study enables a thorough investigation of a problem and can be seen as a project that has a limited time and area to study, according to Bell (2006). This corresponds well with the prerequisites for the project, and it is positive that a deep investigation is made possible since it increases the understanding and ability to evaluate the problem thoroughly. The personnel at the case company are interested in the subject and competent persons can assist in the creation of the model.

Other ways of doing the research, suggested by Patel & Davidsson (2003) are surveys or experiments but neither of these are suitable. The research should be connected to the type of problem and surveys enable studies in big selections. Common tools are questionnaires and interviews. Experiments on the other hand are useful when single factors are studied, experimented with and attempted to control, according to Patel & Davidsson (2003).

2.3 Data collection

In a scientific project, different approaches on how to collect information can be used. Holme & Solvang (1997) describe the qualitative and quantitative approach, and emphasize that they
do not have to exclude each other. They both give a better understanding of the surroundings but in different ways. The qualitative approach is based on interpretations and observations by the researcher, while the quantitative one uses statistical analysis of absolute figures, Holme & Solvang (1997). A case study is generally seen as a qualitative study but it may contain quantitative parts, according to Bell (2006).

Qualitative studies give a good overview and understanding of the problem but require that the studied area is quite small since the method is resource demanding. Holme & Solvang (1997) also mean that qualitative studies may be questioned since they rely on interpretations. These interpretations, in turn, are based on the researcher’s pre-understanding, brought up by Aspers (2007), which includes the knowledge that has been gained during interaction with other people and through theoretical studies. Examples of qualitative techniques are; Observations, flexible interviews and literature reviews. Qualitative data collection will be used in this project, with a small area to study and a relatively long time at hand which will enable deepened knowledge within the specified area.

Quantitative studies on the other hand enable a wider studied area and Holme & Solvang (1997) state that they can be used to make generalizations based on statistics, i.e. to draw conclusions that are valid in more areas than the one studied. One problem with quantitative methods is that not everything can be studied quantitatively however, at least not in a meaningful way. Surveys and experiments are examples of quantitative techniques, Holme & Solvang (1997). Quantitative data will also be collected in this study, mainly consisting of failure reports and statistics on the number of reported failures etc. This data will function as a complement to the gathered qualitative data and enable testing of the model.

When performing a case study it is important to have the ability to separate primary data from secondary data. Aspers (2007) declare that the primary data is generated by the researcher with the purpose of answering a specific question, while secondary data is created by other persons and with other purposes. Thereby, the primary data is more reliable, Aspers (2007). In this case, both primary and secondary data will be used, primary data from e.g. interviews and observations, and secondary data like process documents, scientific articles and literature etc.

2.3.1 Observations

Aspers (2007) describes observations, where the researcher participates in, or observes, the field activities. It is a method that enables understanding of the field. Holme & Solvang (1997) mean that vision, hearing and asking questions are essential when doing observations. They further state that notes must be taken during the observations to make sure that important aspects are remembered. According to Patel & Davidsson (2003), observations may be structured or unstructured. The structured ones are performed when it has been decided which aspects that will be observed and the unstructured are carried out when just about anything is observed in order to increase the knowledge base within an area. The researcher can choose to be a participant in the actions, i.e. to be an active part in the course of events, or to be non-participating where he/she keeps outside the actions and just observes, Patel & Davidsson (2003).

During this case study, participative observations will be a big part of the data collection since the researcher will be present at the case company throughout the study. Questions will be asked and the working procedure when analyzing field data will be observed. This will help in understanding the empirical parts and the problems that can be encountered and thereby also
facilitate the creation of the model. To keep the reliability high, the field notes will be transferred into a computerized document as soon as possible to assure that the researcher does not forget what has been said. Both unstructured and structured observations will be performed. In the beginning, the unstructured ones will constitute the biggest part since it is necessary to understand the overall way of working and later on the observations will be more structured.

2.3.2 Interviews
An interview is an interaction between a researcher and an interviewed individual in which the researcher aims at understanding the other person and the empirical foundation. Aspers (2007) means that there are several kinds of interviews and state that an easy way to separate different types is the level of structure. A structured interview is based on fixed questions, while a semi-structured interview has a set of defined questions but enables the researcher to follow up the given answers. Both of these are mainly deductive and are based on the researcher’s perspective and pre-understanding. The next type of interview structure is the open interview with a defined theme, in which a specific subject is discussed freely. The final structure is the open interview which means that anything that is brought up by the interviewed person is discussed. Aspers (2007) prefers the open interview with a defined theme, which is similar to a normal conversation, and means that it may be preferable to start with that structure to gain understanding after which the questions can be more structured.

In this case, the suggestion by Aspers (2007), to start with open interviews with a defined theme will be followed, which will increase the understanding. When the knowledge has reached a higher level, the questions will be semi-structured to enable obtaining answers on specific questions.

2.3.3 Literature reviews
Patel & Davidsson (2003) mean that a good way of gathering information is through the use of books, articles in scientific journals, reports and the Internet. Books contain models and theories that are fully developed, while the most recent information can be found in articles and reports, Patel & Davidsson (2003). The theoretical framework used in this report will mainly be gathered at the library, primarily focusing on literature about dependability, reliability and field data and via the database ELIN (Electronic Library Information Navigator) which houses scientific articles from several databases and publishers.

2.4 Reliability, Validity & Generalization
Bell (2006) states that it is important to evaluate how reliable and valid a study is. Thurén (2004) means that the reliability signifies if the research can be redone at another time and give the same results. He further explains that reliability implies that the measurements have been performed in the right way. Reliability can be affected by many factors, Bell (2006) implies, e.g. in an interview, the formulation of questions will have a great impact on whether the answers will be uniform or not. Merriam (1994) argue that the general form of reliability is not a suitable measure for qualitative studies, instead the focus should be on creating results that are consistent and can be explained, and that they have a meaning. It is important that assumptions and theories are accounted for, that several methods for data gathering are used and that the data collection procedure is thoroughly described, Merriam (1994). The reliability in this study will be maintained through continuous field notes, which can be gone through
afterwards if necessary and the assumptions and data collection will be explained in the report to increase the understanding. Several data gathering techniques will be used as mentioned above, which will enhance the reliability too. Templates for the semi-structured interviews will also be accounted for.

Bell (2006) furthermore describes validity and means that it is a measure that is used to evaluate if questions that have been asked really helped in answering the big overall question, i.e. if the right things have been investigated. Merriam (1994) mentions that validity can be divided into internal and external, in which the internal validity determines if the results correspond with the reality and if the right things have been measured. If the internal validity is high, so is the reliability. The external validity concerns the possibility to draw general conclusions from the investigation, i.e. if the results can be applicable in other areas. Concerning the internal validity it will be strengthened as the supervisors, both at the company and the university, go through the investigations and give their opinions. The external validity, which has to do with generalization, will be relatively strong since existing theories constitute a great part of the model development. One way of increasing the reliability and validity, according to Merriam (1994), is to use triangulation. That technique implies combining methods for data gathering, such as observations and interviews since they can become powerful tools when used together. Consequently, this methodology will be inspired by, and similar to, triangulation since several data collection methods will be at hand.

Case studies have been accused of being hard to verify and Bell (2006) describes that critics mean that there is a risk of distorted results since only separate cases are investigated and that they cannot be generalized. Others mean that generalization, or at least the ability of relating to other cases, is reasonable within similar areas. Further, case studies can generate new ideas and comparisons between actors, Bell (2006). One way of looking at generalization, according to Merriam (1994), is to let the reader evaluate if the results are applicable in his/her area. However, it is important that the writer gives detailed information about the surroundings and under what prerequisites the study was performed to make the reader understand the results and to be able to evaluate generalization possibilities, Merriam (1994). Even though this case study focuses on one specific company and, as the critics say, may be affected by the company in question, the developed model will be based on general terms as far as possible and therefore it should be applicable in other areas and companies as well. A thorough description of the context of the study will be given to increase the generalization and thereafter the reader can evaluate in what areas the model is useful.

*Figure 2:1* presents a summary of the methodological choices for the report.

![Figure 2:1 – Summary of methodological choices](image)
3 Theoretical foundation

The theoretical framework that is required to grasp the content of the report and the creation of the model will be presented in the following chapter. Continuous and cost-effective improvements are brought up since that will be an essential part of the model, as well as dependability and design which are core aspects in the report. The problems related to data collection and analysis are mentioned. Also, general data need in field reports have been compiled in order to support estimation of which data that is required during dependability evaluations. To find the required data, the analysis need for field data concerning dependability is defined in the subsequent part. Previous experiences in projects similar to this have been included to give some input to the model development. In general, everything in this chapter is brought up with the intention of being used in the upcoming model.

3.1 Continuous and cost-effective improvements

A process for continuous improvements should, according to ISO 9004:2000, contain the following steps:

- Defining reason for improvement
- Evaluating present situation and finding most frequent problems
- Identifying root cause of problem
- Finding possible solutions, choosing and implementing the most suitable one
- Evaluating effect of solution
- Standardizing solution, replacing the old structure
- Estimating success of improvement, investigating if it could be applicable in other areas

Using an improvement cycle is a good way of continuously improving processes in companies. The PDSA (Plan-Do-Study-Act) cycle (also denoted PDCA when Study is exchanged for Check) is described by Bergman & Klefsjö (2007). Initially, in the planning phase, the biggest cause of the problem should be defined. Thereafter, during the do phase, suggested measures to get rid of the problem should be implemented. After the measures have been taken, the success should be evaluated (study phase) and, in case of good results, the new measures should be maintained. In the final, act phase, learning should be acquired to avoid similar problems in the future. In case of success the solution should be standardized and in case of failure the cycle should be performed an additional lap, Bergman & Klefsjö (2007) maintain. This cycle can be repeated over and over again to continuously improve the processes, shifting studied problems over time.

When decisions are to be made they need to be based on facts. This can be accomplished by using suitable analysis tools, statistical techniques and logic. Previous experiences should also be taken into consideration. (ISO 9004:2000) Al-Najjar & Kans (2006) mean that it is crucial to use relevant data to make cost-effective decisions. In case of evaluating the cost-effectiveness, the authors suggest that the economic output before and after the change should be compared. Kans & Ingwald (2008) describe that information and data from all areas related to the subject of study is required to enable cost-effective decision making. Kans & Ingwald (2008) also advocate that translating technical measures into financial ones simplifies the communication between the personnel at the company since it can be understood by everyone, regardless of function. Bergman & Klefsjö (2007) emphasize that the issue that will be most profitable should be taken care of first.
Al-Najjar (2007) explains that the maintenance strategy is part of the company’s overall strategy and point out that it affects the cost-effective improvement possibilities. Many systems are repairable, meaning that they can be restored to perform their function after a failure has occurred, Ascher & Feingold (1984) point out. Repairs can be performed several times but the outcomes can be different though, e.g. same-as-new or bad-as-old, the first indicating complete renewal while the second implies that one small part is replaced and the remaining items are in the same state as before the failure.

3.2 Dependability and design
It is mentioned in IEC 60300−3−1:2003 that, for a system to be dependable, it has to have stated conditions for use and a defined purpose with regards to intended functions. There is also a given procedure for analysis of dependability of a system in the referred standard; First, the system has to be defined, followed by definition of goals and dependability requirements. Then, the dependability should be broken down on the sub-systems. This is followed by analysis of the dependability with help from various techniques. Evaluations on whether the goals are met and if design modifications may improve the dependability in a cost-effective way should also be done. (IEC 60300−3−1:2003) When performing dependability analyses, field data has high importance since it can be used for e.g. justification of design modification, feedback to design and production, maintenance planning and performance follow-up. It can be decided if the analysis should focus on a specific area. By setting up criteria for that area only the failures that fulfill the criteria can be studied. (IEC 60300−3−2:2004) There is not one perfect analysis method for dependability, in most cases several methods have to be used in order to complement each other. Top-down (e.g. FTA and RBD) and bottom-up (e.g. FMEA and HAZOP) techniques combined give possibilities of reaching a complete analysis during the design phase. (IEC 60300−3−1:2003)

IEC 60706-2:2006 point out three main things required of a design. It should; achieve the required performance, be reliable and easy to maintain. Evaluation of this, as well as identification of components that will wear out or cause problems, should be done during design reviews. What is aimed at achieving during the design reviews in general is to evaluate the capability of the design with regards to requirements and to identify problem areas and find solutions, IEC 60706-2:2006. Since the subcontractors have a big impact on many projects, it is proposed in IEC 60706-2:2006 that they should be involved in maintainability planning during the design phase.

Requirements on systems can be either functional or non-functional. The functional requirements are directly connected to the function of the system, while the non-functional are dependent on external constraints and describe the overall requirements, e.g. performance measures concerning safety, reliability, and usability. (Kotonya & Sommerville, 1998)

3.3 Improving the design process
In order to have a well-functioning design process, Shakeri et al. (1999) indicate that the departments within the company that are affected by the design need to be integrated and share information and goals. Frequently, Shakeri et al. (1999) mean that the diverse disciplines have different points of view and thereby have their own goals that may conflict with the final design. Ireson (In Ireson et al., 1996) describe that reliability engineers should function as consultants for the designers and try to anticipate problems with the design. During the design phase, he mentions that the products should be broken down into
subassemblies or components and information about the specific parts are required. In IEC 61160:2005 it is stated that the earlier a design change is initiated in a design review, the better. This due to the increasing cost related to design correction as the process approaches the final design, IEC 61160:2005.

Cui & Khan (2008) have created a model that suggests how to handle design improvements with regards to reliability after a product has been released, with help from field data. In developing the model, a case study was performed at a healthcare company delivering syringes. The suggested model by Cui & Khan (2008) is divided into steps as follows:

1. Define the key metrics to evaluate reliability.
   The measures need to be good indicators of the product’s reliability, based on the resources available and correspond with the objectives of the company.

2. Identify goals for the key metrics.
   Cui & Khan (2008) mean that the goals should be possible to reach but emphasize that they need to be challenging.

3. Collect field data.

4. Analyze the data and create a report.
   Evaluate the performance of the component, subsystem or system. It is suggested that prioritization of design issues can be done within specified time periods.

5. Select and develop projects.
   Prioritize the design projects based on the biggest issues that have been discovered and develop design requirements and new design.

6. Verify the design.
   Test the upgrade. If new problems are discovered, the design needs to be gone through again.

7. Test the reliability.
   Investigate if the modified design performs according to the reliability goals.

8. Validate the new design.
   If problems are discovered, they need to be taken care of. Thereafter a new reliability and validation test can be performed.

9. Update preventive maintenance plan.
   The preventive maintenance plan is updated based on the information in step 2 and 4. It is recommended that this is done within specified time periods.

10. Implement the changes in the field.
    Cui & Khan (2008) mention that documentation has to be done and that proper communication and internal support is required. The communication is brought up as a very important aspect in order to implement new design successfully.

3.4 Finding and securing usable data
Bloom (In Klösgen & Zytkow, 2002) means that data in operational databases often are in bad condition. He declares that there can be several reasons for this, e.g. invalid or missing fields, duplicate data and inconsistencies. Since data records often suffer from errors the data has to be prepared before accurate analysis is made possible, since it is better to have little high quality data than much corrupt data. Initially, the data has to be investigated in order to find missing or incorrect information and then the faults need to be corrected. To be able to correct faults in the reports, deep knowledge about the products and processes that precede the report is crucial. (IEC 60300-3-2:2004) Also Eklöf (1992) bring up the problems of assuring data quality. He describes that the two aspects relevance and accuracy of data should be considered. These main areas can be broken down further where relevance is believed to be
Theoretical foundation

depending on data contents and actuality while accuracy is depending on prejudice and precision.

Many organizations have large databases, containing much potential information, according to Adriaans & Zantinge (1996). They mean that information often is very problematic to get hold of, though, and therefore Knowledge discovery in databases (KDD) and data mining has been developed. Klösgen & Zytkow (In Klösgen & Zytkow, 2002) explain that KDD is a general process for using data to gain knowledge. With help from this process, solutions to problems within the business can be found. Data mining is a central part of this process, Klösgen & Zytkow (In Klösgen & Zytkow, 2002). The concept of data mining is described as finding useful information in large sets of data, in e.g. databases, Awan & Awais (2007) state. A process that aims at standardizing the data mining method, called CRISP-DM (Cross-Industry Standard Process for Data Mining), is described by Awan & Awais (2007:417). It includes the following steps:

1. **Business Understanding.**
   Here, knowledge about the business objectives is necessary. The criteria for success needs to be established, along with requirements, problem definition and planning.

2. **Data Understanding.**
   Collection and verification of data for the project.

3. **Data Preparation.**
   Selection of necessary data, which is cleaned and processed and prepared for the modeling tool.

4. **Modeling.**
   Use of different modeling techniques that are adapted to the project.

5. **Evaluation.**
   Model evaluation based on the success criteria (step 1).

6. **Deployment.**
   Presentation and interpretation of the results from the model utilization to support decision-making.

Sattler & Schallehn (2001) mention that data preparation is an important activity in the CRISP-DM process. This, in turn, can be broken down into defined parts; The data has to be selected through identification of what is relevant for the analysis. Also, data from several sources should be integrated and transformed to fit the analysis tools. In addition, the data needs to be cleaned by e.g. removing disturbances and duplicates and filling in missing values to increase the data quality. Then, the data has to be reduced to make the analysis easier to handle. (Sattler & Schallehn, 2001)

### 3.5 Field data need in failure reports

There are many suggestions on what data that is necessary in failure reports. A summary of some of the available proposals is listed in Table 3:1, where it has been marked with an “x” if the reference brings up that specific area. The authors have been chosen since they discuss the subject in a clear way and bring up why the aspects are important. During the literature review these references were found during searches for “field data”, “reliability”, “collection of data”, “dependability”, “maintenance” etc. in different combinations. The information under “general data need in field reports” in the table is required by one or several authors and is therefore regarded as necessary. This section may be seen as a kind of an analysis, since the authors’ statements have been interpreted and placed in a table under general labels.
To avoid errors during reporting of field data, Smith (2001) recommends that a formal document should be used for gathering of data. Different kinds of data from the field can be collected. It is proposed by Holmberg & Lönnqvist (1997) that the information should be possible to sort, e.g. with help from codes for different attributes. The events should preferably be able to break down into smaller parts based on e.g. types of failures, according to IEC 60300-3-2:2004. Additionally, the failure reporting system should be adapted to the specific aim of the follow-up and the information has to have high quality to enable evaluation, Holmberg & Lönnqvist (1997) argue. The measures that have been decided upon need to be possible to supervise with help from the reporting system.

Moubray (1997) means that it is vital to have contact with the personnel that operate and maintain the equipment to get reliable failure data since they have genuine knowledge within the subject. Also, Smith (2005) upholds that the service personnel need to be informed about the importance of reporting failures. He means that the best way of motivating the personnel is to regularly send summaries to make them appreciate the use of it.

In ISO 14224:2006, prioritization of data is suggested to clarify the importance of each type. The most important class is the compulsory data which should be covered to almost 100 %. Next is the highly desirable data, which should have about 75 % coverage or more. The least important, desirable data, should be covered to at least 50 %. (ISO 14224:2006)
3.6 Analysis of field data
When the field data has been gathered, it has to be analyzed. The nature of failures and their frequency can be calculated and ranked in descending order based on frequency or on frequency multiplied with cost, Smith (2001). In this, Pareto analysis and other explorative data analysis methods are useful. Calculating the number of events during a specified period of time is a basic level of analysis that can help in identifying the areas that need to be focused on, IEC 60300-3-2:2004. Also IEC 61160:2005 and Ireson (In Ireson et al., 1996) bring up the importance of measuring the failure rates. Ireson (In Ireson et al., 1996) means that failure rates for each component can be used to identify the most important issues. Besides from this, the data can be used to evaluate if the failure frequency is increasing or decreasing, according to Smith (2001).

The field data should also support reliability measures, according to Johansson (1997) and IEC 61160:2005. In the standard IEC 61160:2005, which specifically concerns design reviews, it is suggested that it should be discussed if reliability and cost go in line with the predefined goals. Ireson (In Ireson et al., 1996) states that it is useful to find the failures that arise during use to enable making more reliable products and uphold that failure analysis documents can clarify the importance of change. Maintainability is another measure that is desired to calculate, Johansson (1997) and IEC 61160:2005. More explicitly, the last mentioned reference implies that the level of maintenance and the maintainability requirements should be discussed, as well as the use of replaceable units and the ability to perform failure diagnosis. It is also desired to calculate availability, according to Johansson (1997) and IEC 61160:2005.

Important aspects to take into consideration, stated in IEC 61160:2005, are measures showing the most common causes of failures. Ireson (In Ireson et al., 1996) means that failure causes for each component are useful for identifying the most important matters. Ireson (In Ireson et al., 1996) furthermore mentions issues that are related to human beings, such as common misuse by customers, effectiveness of the field service personnel and failures due to inadequate operation and maintenance manuals, and means that this should be considered during the analysis. IEC 61160:2005 bring up installation, maintenance and users and their effect on reliability and point out that these aspects should not be forgotten. Further, unacceptable downtime should be accounted for. Overall, comparisons to similar products are helpful, IEC 61160:2005. These aspects too have to be supported by the field data reports. If condition monitoring is included (such as the in-flight data mentioned by Ortiz et al., 2008) this data can function as a complement to the field data and facilitate the analysis further.

Complicating issues during evaluation of repairable systems reliability, mentioned by Ascher & Feingold (1984), are that repairs may be incomplete, improper or on the other hand particularly effective. Failures in a system can also cause failures of other parts, stresses can be affected by e.g. on/off cycles instead of operating time, repairs may be adjustments and not replacements, among others.

3.7 Previous experiences
Jauw & Vassiliou (2000) have presented the implementation of a system called PQTS, or Product Quality Tracking System, and some of their experiences may be used as inspiration in this project. When the creation of the system was initiated, decisions were made on what data that was required in order to do proper analysis. Consideration was taken to the customers and the reports that they might demand and discussions were held with engineers and managers to
ascertain what kind of analysis they needed. After the data had been defined, the different data sources were connected to each other and it was decided what the reports would look like. Jauw & Vassiliou (2000) enhance that it is important to have user-friendly and easily understood reports for them to be useful.

In the paper by Ortiz et al. (2008), the aircraft industry is in focus and the importance of integrating data from multiple sources is emphasized since it gives a good overall picture. In doing that, valuable data for the engineers and maintenance staff can be gained, e.g. information that helps in defining the best time to perform maintenance. The data that is regarded in the paper is in-flight data records and maintenance action information. (Ortiz et al., 2008)
4 Model development

In this section, a model showing which data that are needed and how these should be used in order to improve design of existing and future product generations is developed. The data need has been included in the working procedure model where the key measures are defined in step 1 and the data needed to evaluate these measures are presented in step 3. During the development, theories accounted for in the theoretical foundation chapter have been compiled and some own apprehensions have been added. When using the theory, the authors in question are mentioned. In case no reference is stated, it should be interpreted as own discussions by the researcher. To get a model that is suitable in real life, experts at the case company have been consulted and read it through.

When the theories from the previous chapter had been brought together, the following way of working was concluded. The core inspiration has been Cui & Khan (2008) and the other theories have been used as a complement. Even though the model might seem similar to the suggestion by Cui & Khan (2008), at least in the beginning, this model goes deeper into each step defining what is required and it takes the working procedure further than they do since follow-up and storage of solution is considered. Furthermore, this model is regarded as a continuous improvement cycle, inspired by the PDSA cycle described by Bergman & Klefjö (2007). In the model by Cui & Khan (2008) one big aspect, business performance which is related to cost-effectiveness, is also lacking and therefore this point of view has been added.

The developed model is presented here;

1. Define key measures based on:
   - Defined area of study
   - Objectives
   - Identified relevant data (founded on needs from e.g. customers, managers, engineers)

In step 1 the key measures should be identified. When defining key measures for a specific kind of follow-up, the area in focus and the intended objectives must guide the decisions (Awan & Awais, 2007; Cui & Khan, 2008; IEC 60300−3−1:2003). To find the key measures, it has to be clear which area that is to be studied and who should benefit from the measures (in this case the data that is relevant for engineers/designers). The key measures concerning dependability improvements are accounted for below.

Since it is part of the problem formulation to find the data need for dependability related design improvements, this part has been performed with help from theory in this report. In other cases, the persons that are supposed to use the field data information, e.g. persons in charge of design, can define which key measures that are necessary.

Consequently, the first step that needs to be taken is to identify what analysis, i.e. which key measures, that are called for to evaluate dependability and in the end support design improvements. After that, the data that needs to be available in order to perform that analysis must be defined, using a top-down method. The data will be defined in step 3. Accordingly, the suggestion by Holmberg & Lönnqvist (1997), to adapt the follow-up to its specific objectives, will be regarded. In this case, the aim is to use field data to improve the dependability related design of existing and future products to make them more cost-effective. Therefore focus will lie on data and analysis that concerns that area. The following key measures (Table 4:1) are assumed to be essential for analysis of dependability related design, mainly based on section 3.6 in the previous chapter, but also partly on 3.2;
### Key measures

<table>
<thead>
<tr>
<th>Key measures</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure intensity</td>
<td>IEC 60300-3-2:2004; IEC 61160:2005; Ireson et al., 1996; Smith, 2001</td>
</tr>
<tr>
<td>Evaluation if failure intensity is increasing or decreasing</td>
<td>Smith, 2001 (he uses the term “frequency” instead of “intensity”)</td>
</tr>
<tr>
<td>Most common failure causes</td>
<td>IEC 61160:2005; Ireson et al., 1996</td>
</tr>
<tr>
<td>Downtime due to substandard acts</td>
<td>IEC 61160:2005; Ireson et al., 1996</td>
</tr>
</tbody>
</table>

*Table 4.1 – Key measures required for dependability evaluation*

There is no relative order among these measures which means that the sequence in which they are investigated is insignificant. Yet, there may be a possibility that downtime due to substandard acts (which in this case is regarded as e.g. misuse or poor maintenance) may be found when the most common failure causes are investigated. Naturally, users of the model have the ability to choose the key measures out of these that they believe are important. There is no need to calculate/evaluate key measures that are not believed to be useful. In that case it should be considered that the data need (identified in step 3) might be affected though.

2. **Identify requirements and criteria for success of key measures**

In step 2, goals for the defined measures have to be clarified to enable relevant evaluation, Awan & Awais (2007) and IEC 60300-3-1:2003. If no goals or requirements are set up for the measures, the follow-up will not show if the results are satisfying or not. There has to be something to compare the outcome to. Cui & Khan (2008) mean that the goals should be possible to reach but point out that they need to be challenging. The requirements can be both functional and non-functional, but in this case it is assumed that non-functional requirements will be dominating since, as Kotonya & Sommerville (1998) explain, they control overall performance measures and are therefore connected to dependability.

3. **Collect and select relevant field data (from more than one data source if possible)**

- Prepare data to make it easy to handle and analyze (reduce, clean, find incorrectness etc.)
- Break down data into sub-systems/components

Step 3 consists of the collection of field data, which aims at finding and selecting the relevant data and preparing it. In the cleaning process the data quality should be increased by removing duplicates, filling in missing values and removing inaccuracies. (Bloom, In Klösgen & Zytkow, 2002; IEC 60300-3-2:2004; Awan & Awais, 2007) It is essential to know which data that are vital for the analysis to facilitate reduction of the data set, Sattler & Schallehn (2001) emphasize, and it should be reflected upon whether the data are relevant and accurate since Eklöf (1992) means that the data quality may be poor in many cases. It can also be decided to focus on a specific area. By setting up criteria for these areas the data set can be limited to failures that fulfill the criteria. (IEC 60300-3-2:2004). Having defined requirements and problems, which is proposed in the CRISP-DM process described by Awan & Awais
(2007) (see theoretical foundation, section 3:4), can be helpful. When the data are gathered, it is positive if more than one data source is examined (such as data from both condition monitoring tools and maintenance reports), as Ortiz et al. (2008) mention. It is also helpful if the information about failures is broken down on specific components since that is useful when modifying the design, Ireson (In Ireson et al., 1996). Furthermore, the data have to be made suitable for the chosen analysis, Sattler & Schallehn (2001). In general, it is important for the people in charge to realize the importance of follow-up and continuous improvements in order for the analyst to obtain the required resources. The data collection and analysis is time-consuming, see Sattler & Schallehn (2001), and this has to be understood and accepted by the management.

As a part of the problem formulation, the field data need for dependability related design improvements will be defined here. In case of other key measures, the same procedure to find the data need can be used. The measures should be adapted to the specific project and if not all of the identified key measures are regarded as necessary, the ones that are not useful can be removed. The field data in the reports that are believed to be important in order to calculate/evaluate the key measures in this case have been compiled in Table 4.2, where the correlation between general data need in field reports (which was defined in the theoretical foundation, section 3.5) and the key measures from step 1 have been clarified. The author has made own appreciations on the correlation, based on the data that is required for calculating/evaluating the actual output of each key measure.

<table>
<thead>
<tr>
<th>General data need in field reports</th>
<th>Key measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report no.</td>
<td></td>
</tr>
<tr>
<td>Service personnel identification</td>
<td></td>
</tr>
<tr>
<td>Identification of failed product</td>
<td>x x x x x x x</td>
</tr>
<tr>
<td>Time of occurrence of failure</td>
<td>x x x x x x x</td>
</tr>
<tr>
<td>Identification of failed system</td>
<td>x x x x x x x</td>
</tr>
<tr>
<td>Identification of failed component</td>
<td>x x x x x x x</td>
</tr>
<tr>
<td>Description of fault</td>
<td></td>
</tr>
<tr>
<td>Failure consequence/category</td>
<td>x x x x x x</td>
</tr>
<tr>
<td>Operating conditions</td>
<td>x x x x</td>
</tr>
<tr>
<td>Symptoms of failure</td>
<td></td>
</tr>
<tr>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>Time to complete service</td>
<td>x x x x</td>
</tr>
<tr>
<td>Type of inspection</td>
<td></td>
</tr>
<tr>
<td>Maintenance action/rectification</td>
<td>x x x x</td>
</tr>
<tr>
<td>Equipment used</td>
<td></td>
</tr>
<tr>
<td>Spares used</td>
<td></td>
</tr>
<tr>
<td>Time in use before failure</td>
<td>x x</td>
</tr>
<tr>
<td>Root cause of failure</td>
<td>x x</td>
</tr>
</tbody>
</table>

Table 4.2 – Correlation between data in field reports and key measures

This table may be questioned since it is created based on subjective judgment. As an example; in some cases it can be necessary to know e.g. the root cause of failure to evaluate reliability
and availability if failures are caused by external factors and therefore should not be included in the estimation of the product performance. However, this has not been considered since the actual outputs of the measures are aimed at. In case the measures turn out to be dissatisfying the most common failure causes, which is another key measure, can be investigated, and thereby it can be examined whether other factors have caused some of the failures. It is also possible that more information about the maintenance, e.g. about equipment and spares, can be useful to evaluate maintainability and most common failure causes but it is believed that the data need that has been chosen will be sufficient for this purpose. In general, this distribution should be relatively true but if not agreed upon, this too can be adapted to the specific project.

It was highlighted that downtime due to substandard acts should be accounted for and that aspect will not be easily gained in the reports. The failures have to be analyzed to find the ones that are caused by substandard acts. If e.g. misuse or poor maintenance is suspected, concerned failures should be investigated carefully. In this category information about use and the human impact is included. Downtime due to substandard acts could be comprised by the aspects brought up by Ireson (In Ireson et al., 1996), i.e. performance of service personnel, failures caused by inadequate operation or maintenance manuals or misuse when the product is in operation. It should only be relevant to investigate this if there is reason to believe that irregularities are a fact. In case the outputs of the other measures are satisfactory, this might not have a particularly high importance.

Based on the compilation in Table 4:2, the data that are necessary in order to analyze the required key measures are accounted for in Table 4:3. To clarify the importance of data, it has been divided into three categories; Compulsory, Highly desirable and Desirable, as suggested in ISO 14224:2006. The classification has been done by calculating the number of x’s in each row in Table 4:2. The data that is regarded as compulsory has at least 5 x’s, the highly desirable has at least 3 x’s and the desirable data has at least 1 x. The number of x’s shows how many key measures that require that specific data input, meaning that many x’s makes the data more important. Consequently, the required field data input to calculate the key measures for dependability related design improvements are;

<table>
<thead>
<tr>
<th>Field data needed for dependability related design improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compulsory</td>
</tr>
<tr>
<td>- Identification of failed product</td>
</tr>
<tr>
<td>- Time of occurrence of failure</td>
</tr>
<tr>
<td>- Identification of failed system</td>
</tr>
<tr>
<td>- Identification of failed component</td>
</tr>
<tr>
<td>- Failure consequence/category</td>
</tr>
</tbody>
</table>

Table 4:3 – Field data needed for dependability related design improvements.

The compulsory data is required to find the intensity of failures and to show which part of the product that has failed. “Failure consequence/category” has such high importance since it
determines how big impact the failure has and if it affects the reliability and availability. Logically, it is worse to have a failure that causes total break-down or stoppage than a small failure that can be taken care of during planned maintenance and does not affect the daily operation. The “failure consequence/category” is also useful for evaluation from a cost-perspective since it can indicate how severe the failure is, e.g. if it has caused stoppages, damages etc.

In case of little available field data that is to support design improvements, the data need can be narrowed down to only including the compulsory data, even though it is undesirable. With that information, the intensity of failures for both systems and components can be ranked to see the most critical issues. Finding the most frequent failures during a defined period of time can help in identifying the most important areas to focus on, according to IEC 60300-3-2:2004. If the costs of systems/components and replacements can be collected from other data sources, the frequency of failures can be multiplied with cost, as Smith (2001) proposes, thereby ranking the most important issues. When the essential concerns are found, they can be examined thoroughly to find the root causes outside of the data records, via e.g. communication between engineers and service personnel. “Failure consequence/category” is needed in order to facilitate evaluation of the failures. Knowing the severity of failures is useful to make sure that serious failures are not left behind even though they may have relatively low failure intensity.

The data should be found in formal documents, as suggested by Smith (2001), and codes should be used when possible, according to Holmberg & Lönnqvist (1997), to ease sorting of data. Further, the data must be possible to break down, IEC 60300-3-2:2004, and be easily compared to similar products, IEC 61160:2005. The defined data should be entered by the service personnel. There are some fields that may be hard for them to fill out however, mainly “time in use before failure”, “root cause of failure” and “operating conditions”, see Johansson (1997) and Moubray (1997). As the quality of the input data has to be high (Holmberg & Lönnqvist, 1997 and IEC 60300-3-2:2004), it is essential to forward this need to the service personnel entering the field data. Moubray (1997) suggests that the contact with service personnel is of high importance, and this has to be considered when creating templates for field reports. Still, if there are shortcomings in the field reports, a decision has to be made. Either effort is put on improving the reports with help from service personnel in order to support efficient follow-up, or the shortcomings are disregarded and the available data is utilized the best way possible.

One additional aspect that may be added, or at least considered is the maintenance strategy, which, as Al-Najjar (2007) explains, affects the possibilities of making cost-effective improvements. This cannot be found in the failure reports though. It should also be regarded if the systems are repairable and if the repairs make the systems same-as-new or bad-as-old, which is an aspect brought up by Ascher & Feingold (1984).

4. **Analyze the field data**
   - Calculate key measures/levels of significance

When the data is to be analyzed in step 4, the analysis should be adapted to the specific project, Awan & Awais (2007) uphold. However this has to be considered carefully since the analysis should be standardized to the extent of facilitating comparisons of outcomes in different projects. In this case, supporting design improvements, initial ranking of the most frequent or severe issues, possibly using Pareto analysis (Smith, 2001), can be a good start. In
the analysis, the present situation and the most frequent problems should be brought up as well as identifications of the root causes of failures, ISO 9004:2000 and Bergman & Klefsjö (2007). This stage is similar to the Plan phase in the PDSA cycle. Awan & Awais (2007) mean that the goal of the analysis should be to calculate the key measures that have been defined in step 1. It should be known by the analyst that there are many issues that can complicate the analysis if the systems are repairable. Some of them are mentioned by Ascher & Feingold (1984) and presented in the theory chapter. Cui & Khan (2008) mean that a schedule can be made, defining how often analysis should be done. In fact, both collection and analysis of data can be done within specified periods of time, e.g. once a month.

5. **Create reports presenting key measures**

After analysis, the information should be compiled in easily understood reports, Jauw & Vassiliou (2000) stress, and sent to concerned personnel. This is done in step 5. Also Awan & Awais (2007) propose the use of reports which should contain a presentation and interpretation of the results from the analysis to support decision-making. To stress the cost-effectiveness, the financial aspect should be added, since Kans & Ingwald (2008) mean that it can be understood by everyone. The economic output before and after the change should be discussed. Smith (2005) means that a good motivation for the service personnel can be to send them summaries to make them appreciate the usefulness of their work.

6. **Evaluate situation/Determine improvement objectives**

Step 6 uses the reports as a support, and the situation can be evaluated with help from the predefined key measures. According to IEC 60300−3−1:2003, it should be evaluated whether the goals are met at the present and if design modifications may improve the dependability in a cost-effective way. In case no improvements are necessary, this will be the last step.

7. **Choose most cost-effective improvement object on a well-founded basis**

- Motivate in what way the improvement will be beneficial

Based on the evaluation in the previous stage, the most crucial improvement objects can be defined in step 7, as Cui & Khan (2008) suggest. The issue that will be most profitable to deal with should be chosen first, Bergman & Klefsjö (2007) uphold. It is important that this decision is based on well founded information and that the cost-effectiveness of the dependability improvement is regarded. This will be aided by the reports. As the decision needs to be cost-effective, the data should be relevant and all related areas should be considered, according to the recommendation by Kans & Ingwald (2008). In ISO 9004:2000 it is pointed out that the reason for improvement should be clarified. The importance of change can be made clear with failure analysis records, according to Ireson (In Ireson et al., 1996).

8. **Develop/update new design**

- Based on requirements/significant improvements

Subsequent to this stage, in step 8, the responsibility is on the engineers to develop an alternative, better, design suggestion that is in accordance with given requirements, ISO 9004:2000. The improvement possibilities defined in step 7 must be regarded. Techniques such as FTA, RBD, FMEA or HAZOP, can be useful during the design phase for deeper investigation of dependability issues (IEC 60300-3-1:2003). Ireson (In Ireson et al., 1996)
proposes that the reliability engineers should function as consultants for the designers/engineers. As stated in IEC 61160:2005, design changes should be done as early as possible in the design procedure, and therefore the reliability engineers should give opinions on the new design when it is in progress. Shakeri et al. (1999) mean that the departments within the company that are affected by the design need to be integrated and share information and goals in order to have a well-functioning design process. This can be accomplished through design reviews where all concerned parties are participating. In the design reviews it should, as stated in IEC 60706-2:2006, be overhauled if the required performance will be fulfilled, if the new design will be reliable and maintainable and if some components will cause more problems than others. Solutions to potential problems should also be discussed and it is positive if the subcontractors can be involved, in one way or the other, IEC 60706-2:2006.

9. **Analyze new design**
   - Examine suggestions thoroughly
   - Identify most suitable solution (if there are several) based on key measures and cost-effectiveness
   - Test and evaluate how dependable the new design is (if possible)

In step 9 the design suggestion should be gone through thoroughly. After analysis of the design suggestions, if several, the most suitable solution should be identified based on the key measure goals and the cost-effectiveness, ISO 9004:2000. During design reviews it can be discussed if all dependability requirements are fulfilled and if the change goes in line with the cost objective, as mentioned in IEC 61160:2005. If possible the design should be tested, according to Cui & Khan (2008).

10. **Implement the solution**
   - Create documentation
   - Cooperate within the company

Step 10 includes the implementation of the new solution, when it is applied in reality. This can be resembled with the do phase in the PDSA cycle presented by Bergman & Klefsjö (2007). To have a successful implementation, it is crucial to cooperate and communicate between the different functions at the company and to create necessary documentation, as suggested by Cui & Khan (2008).

11. **Estimate success of solution. If successful – standardize it**

The estimation of success is done in step 11, similar to the study and act phase in the PDSA cycle. In case the new design is regarded as successful from a dependability and cost-effective point of view it should be standardized to make sure that it will be used in future products, ISO 9004:2000 and Bergman & Klefsjö (2007).

During discussions with an expert at the case company, an additional point was added;

12. **Store the solution for future reference, both in case of success and failure**

The last phase of this cycle, step 12, is to store the solution in an easily accessible place in order to either promote or prevent a similar solution in the future. If the new design is unsuccessful, the cycle has to be repeated from step 8. Since this step of storing the solution
was added, it would be natural to add utilization of previously stored information in the preceding steps. The most suitable steps to assimilate feedback from previous experiences should be step 7 and 8, since that includes choosing improvement object and starting to work on a solution, and during those phases the investigation should be deep-going.

This model can be seen as a continuous improvement cycle, like the PDSA cycle described by Bergman & Klefsjö (2007) where point 1 and 2 are outside of the cycle, not necessary to be redefined every lap, while the remaining parts are done whenever it is believed to be necessary, see Figure 4.4. As this is a new model, created in this report, it should be given a name. Accordingly it will, simply and unsophisticated, be called the Design Improvement Cycle (DIC) in the future.

Figure 4.4 Design Improvement Cycle

The DIC has been created with the purpose of making cost-effective design improvements related to dependability with help from field data. However, the procedure can be used for design improvements with other purposes as well, the only thing that has to be regarded is to change the key measures and the data need to make them suit the specific area of study.
5 Empirical findings

This section will present information about the case company and a project that will function as a reference project when the model will be tested in the next chapter. General information about RAM/LCC work, field data follow-up and the current work with design improvements at the company will be given to support the analysis and make it easily comprehensible. The information has been obtained in discussions with personnel at the Design Assurance and Product Safety department, more specifically the manager, a specialist and RAM/LCC engineers. Some terms that appear in this chapter may require a translation and therefore a brief English-Swedish dictionary can be found in Appendix 1.

5.1 Bombardier

Bombardier Transportation (BT) is part of the global transportation corporation Bombardier Inc. The corporation has two business areas; Aerospace and Rail Transportation where BT constitutes Rail Transportation. They have been acting on the rolling stock market since the 1970’s and have representatives in 35 countries, of which Sweden is one of the main countries. (www.bombardier.com)

The site in Västerås, Sweden, has about 1000 employees. It started as a part of ASEA in 1883 and was acquired by BT in 2001. Their main products and services provided are Intercity and Regional trains, such as the Oeresund and Regina trains, Metros, Light Rail Vehicles, Propulsion and Train Control systems, Total Transit systems and Services. (www.bombardier.com) The Passenger division at BT works according to a matrix organization, with the line organization on one hand and project organizations on the other.

At the department for Design Assurance and Product Safety at BT in Västerås which is part of the Passenger division, there are four functions; “Reliability Availability Maintainability and Life Cycle Cost” (RAM/LCC), “Safety”, “Type testing” and “Requirement management”. The field data follow-up is a responsibility of the RAM/LCC function, which has five employees. BT is a suitable case company to test the developed model on, since they have an extensive database with field data reports but feel that they do not make full use of it for various reasons, such as the huge amount of information that require extensive analyses. Also, pieces of information about failures are sometimes missing, there are uncertainties about the accuracy of the information and difficulties to interpret the information.

There is a general process for RAM/LCC at the company, accounted for in an internal document called “Procedure, Design for RAM/LCC”. The objective of that document is to substantiate the roles and responsibilities, processes, activities and tools that BT uses to ensure that RAM/LCC requirements are followed within all BT projects, products and markets. In this document it is described that, when a design has been developed to a certain level, the RAM/LCC department shall evaluate it from a RAM/LCC point of view and send feedback to the other parts of the project organization. The balance between RAM and costs for maintenance and hardware needs to be found. During the realization phase, the RAM/LCC documents are updated and the product performance realized. Finally, in the field support phase, it is established whether the products fulfill the requirements or not. (Procedure, Design for RAM/LCC).
5.2 The C20 project

During 1995 Bombardier (which at that time was called ABB Traction which later became Adtranz and after that Bombardier) received an order from the local transporting company (SL) in Stockholm on new subway trains. A new construction, the subway train C20, was developed and the deliveries were conducted between 1997 and 2004. (Fordonsbeskrivning Tunnelvagn C20) A picture of C20 is presented in Figure 5:1.

A C20 train consists of one to three 3-car train units and each unit has 128 seats. In total a unit can take 414 passengers. The maximum speed in traffic is 90 km/h. (Fordonsbeskrivning Tunnelvagn C20)

The vehicle is divided into different systems in the following structure, which is similar to the structure on most products delivered by BT (Figure 5:2). Each system has its own system code:

```
0. Vehicle
   1. Carbody
   2. Bogies & running gear
   3. Power supply
      3.1 Line voltage system
   4. Propulsion
      4.1 Drive system
      4.3 Elec power conversion
   5. Auxilliaries
   6. Braking
   7. Interiors
      7.1 Interior architecture
      7.2 HVAC
      7.6 Ticketing
      7.7 Lighting
   8. Control & communication
      1.1 Body structure
      1.2 Exterior aesthetics
      1.3 Exterior doors
      1.4 Couplers
      1.5 Gangways
      1.6 Window units
      1.7 Body additions
   5.1 Air supply system
   5.3 Battery system
   5.4 Aux elec system
```

Figure 5:2 – System structure C20 (Fordonsbeskrivning Tunnelvagn C20)

According to the contract between BT and the customer SL, a failure is defined as a deviation which, at some time, requires rectification. In this, deviations discovered during preventive
Empirical findings

Failures are measured in terms of failures per million kilometers (FPMK) and the following requirements were agreed upon in the contract:

1. Stoppage in traffic > 10 min: \( \leq X,X \) FPMK
2. Traffic disturbances, i.e. failures that result in that the train is taken out of traffic, is exchanged or causes a traffic stoppage > 10 min \( \leq XX,XX \) FPMK
3. Total failure intensity: \( \leq XXX \) FPMK
4. MTTR should be: \( \leq X,X \) hours
5. XX% of all failures should be remedied within one hour
6. Time to repair a single fault should be: \( \leq X \) hours

The failure category that is the most critical to the customer SL is failures that cause traffic stoppage of more than 10 minutes. That is considered being worse than taking the trains out of traffic or exchanging them, which normally can wait until the end of the trip or until the end of the day, or sometimes even wait for one or more days. In case of stoppage failures, the operator of the trains often has to take the trains out of operation and exchange them as quickly as possible in order to avoid severe disturbances in traffic. The headway, i.e. the time between trains to the stations, is crucial when evaluating the severity of failures, since it is more severe if a certain failure in one train causes delays to subsequent trains than if the rest of the traffic is unaffected. It is believed by a RAM/LCC engineer that the headway will become shorter and shorter over time, placing higher demands on future Metro trains. The reason being that a shorter headway results in a higher traffic capacity i.e. more passengers can be transported per hour at peak traffic, and this is of major importance to the Metro operators.

Regarding the maintainability measures it should be noted that it is mentioned in the contract that they “should” be fulfilled. It is also stated that the trains are in warranty for two years or until they have run 150 000 km, whichever comes first. During the warranty period, BT is responsible to repair all failures that are considered as warranty failures. Warranty failures are important to keep track of, according to a RAM/LCC engineer, and they are used to calculate the failure rates for the failure categories such as “Stoppage in traffic” and “Traffic disturbances”. In the C20 project there is also a “Systematic failures” warranty and if such failures are discovered on the products, the errors shall be corrected on all products supplied, and the warranty time for the affected products are prolonged. Systematic failures are failures referable to design, material or workmanship that appear on more than an acceptable number of products during a certain period of time. Corrective actions shall be corrected by the supplier at his own expense, on all products supplied. The above period of time is often identical to the warranty period. Systematic failure warranty is regularly used by customers in order to avoid problems with excessive failure rates during the lifetime of the products. In the contract, there is no availability requirement. Definitions, time periods and acceptable numbers of failures are often different from project to project, a RAM/LCC engineer emphasizes. Actually, there is much dissimilarity in different train projects. Each project has, to a certain extent, its own requirements, terminology etc.

Besides from the mentioned demands, BT has an LCC commitment that includes the costs for energy during operation as well as maintenance of the trains during their life time. In the LCC model for C20 the biggest part of the costs are related to maintenance. Aspects like annual maintenance cost, total corrective and preventive maintenance cost, kilometer dependent maintenance and inspections, among others, are included in the maintenance calculations. A RAM/LCC engineer explains that the goal from the company’s point of view is to fulfill the requirements stated in the contract, but not essentially to exceed them. Concerning the LCC
commitment, the main interest is to attend to the failures that generate the highest cost, e.g. due to maintenance, not necessarily the ones with the highest intensity, even though the failure intensity can be used to indicate the most significant improvement objects. Finding the root cause of the most frequent failures within the most severe failure categories are of interest since that indicates which improvements that can be done if the performance has to be improved in order to live up to the contract. Also failures that are caused by e.g. misuse or poorly performed maintenance can be included in the investigations.

The train units are repairable systems, and although not certain, a RAM/LCC engineer believes that the preventive maintenance on C20 is performed with fixed intervals, most likely based on traveled distance, which indicates scheduled maintenance. The reason that this is slightly unclear is that the maintenance is taken care of by an external actor in this project. In each project a maintenance plan with e.g. defined preventive maintenance intervals is supplied by BT, as well as maintenance manuals. That information is used by the operator and the maintenance provider to finalize the maintenance strategy. A combination of scheduled maintenance with fixed intervals and a balanced (also called split) maintenance is another alternative that may be used. Balanced maintenance implies that one divides certain scheduled maintenance activities into several smaller portions that are carried out when the trains are available for maintenance. This has the advantage that more trains will be available for operation compared to the conventional scheduled maintenance philosophy.

5.3 Field data follow-up

Field data analysis can support different processes at BT. Either, it can function as an aid for predictions when making bids, it can be used for project follow-up, it can support the FRACAS process to improve present projects, or it can enable improvements of future projects. Hence, the field data analysis can result in design improvements and retrofits (changes in design after it has been accepted) to the delivered trains when it is required, as well as improvements of trains/systems/products of the same type that will be delivered in the future. At the present, the field data is mainly used for follow-up to document the performance and show it to the customers though, according to the manager. Thereby it has more of a documenting nature than being a support for future improvements. Right now, the manager explains that there is no actual feedback to the projects.

When performing field data follow-up at BT, two optional programs/databases can be used at the company. Either the in-house developed database PREMAX, which is accessed through Lotus Notes, or the MAXIMO system, which is used for maintenance by BT. One of these is used at a time, i.e. they are not used simultaneously, according to the manager. The personnel concerned with design, including RAM/LCC, in Sweden use PREMAX. The main reason is that it is considerably cheaper and less complex to use than MAXIMO. However, the service division, i.e. the division performing the warranty maintenance of trains, use MAXIMO as their main tool in carrying out the maintenance. Every warranty failure that is attended to during the warranty time is required to be documented in PREMAX, since the warranty repairs have to be controlled. The data can, from PREMAX, be exported to an excel sheet and thereby enable statistical evaluation, a RAM/LCC engineer describes. By the use of system codes, which are presented in Figure 5:2, the system and sub-system failures can be traced. Besides from that, information about the document (creator, date etc.), the project and vehicle, basics about the failure (short description, warranty y/n, supplier of component/system, fault class, time to perform maintenance including work hours, trouble shooting and function control hours etc.), customer references, symptoms/events, causes/reasons, actions taken and
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in some cases additional information is presented in PREMAX. However, all fields are rarely filled out. The time to perform maintenance that is reported in PREMAX for the C20 project is not directly comparable to the maintenance time in the contract since the time in PREMAX include all time to do the repair (i.e. getting material and maintenance instructions etc.) while the contract only includes the time to do the actual repair, according to a RAM/LCC engineer.

The Product Introduction (PI) department is responsible for commissioning of the trains and support to the customer regarding operation and maintenance matters. This means that they are accountable for the warranty repairs (they purchase the maintenance from the Service department) as well as spare parts management, customer documentation, training of the customers etc. They use PREMAX and similar tools, fill in some of the information there, and put together information about failures.

In PREMAX, failures are divided into categories to show the severity of failure. The same internal categorization is used in several projects to enable comparisons between projects. The following internal categories are used (Table 5:3);

<table>
<thead>
<tr>
<th>Internal failure categories</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Failure category</strong></td>
</tr>
<tr>
<td>10. Significant</td>
</tr>
<tr>
<td>20. Major</td>
</tr>
<tr>
<td>30. Medium</td>
</tr>
<tr>
<td>40. Minor</td>
</tr>
<tr>
<td>50. Third party</td>
</tr>
</tbody>
</table>

Table 5:3 – Internal failure categories in PREMAX

In the C20 project there are also external failure categories. These are more well-connected to the requirements in the contract, see Table 5:4. In the field data reports in PREMAX both external and internal categories are accounted for mostly, but in some cases the failure categories are not specified.
### External failure categories

<table>
<thead>
<tr>
<th>Failure category</th>
<th>Failure mode</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>External cause</td>
<td>Failure due to external cause, e.g. vandalism, climate conditions that are not according to specifications, etc.</td>
</tr>
<tr>
<td>21</td>
<td>Stopping failure</td>
<td>Relevant failure causing stoppage in traffic for more than 10 minutes. (Connected to requirement 1 in section 5.2)</td>
</tr>
<tr>
<td>22</td>
<td>Traffic disturbance</td>
<td>Failures causing the train to be taken out of service, train exchange or traffic including stoppage for more than 10 minutes. (Connected to requirement 1-2 in section 5.2)</td>
</tr>
<tr>
<td>23</td>
<td>Total failure rate</td>
<td>A defect which, sooner or later, requires a corrective action, including defects discovered during scheduled maintenance. (Connected to requirement 1-3 in section 5.2)</td>
</tr>
</tbody>
</table>

Table 5:4 – External failure categories in PREMAX for the C20 project

One big problem during follow-up of field data from the service workshops is that inaccuracies and insufficiencies are very common, according to a RAM/LCC engineer. When the data is gone through, it has to be investigated and cleaned thoroughly in order to conduct sensible analysis. It has been discovered at the company that many of the failures that are reported are caused by external consequences, such as insufficient maintenance according to plan, misuse by customers etc. and this issue is difficult to substantiate without thorough analysis. This is mentioned by both the manager and a RAM/LCC engineer. A RAM/LCC engineer brings up that each single failure has to be gone through thoroughly in order to find out whether misuse or poor maintenance has caused the failure. This can be discovered by studying maintenance instructions which specify how the maintenance should be performed and comparing that to what actually has been done at the workshop by conducting visual inspections. As an aid to this, information in the databases can be used as well since the reported failures should be the starting point of the investigations. It is easier to find the reasons to failures if they are studied as soon as possible after occurrence, a RAM/LCC engineer emphasize. Additional information that can be used as a complement to field data when thorough investigation of failures is required is the EDGAR function within the Train Control Management System (TCMS). Via EDGAR, detailed data that has been logged during operation of the train can be extracted and investigated, according to a RAM/LCC engineer. EDGAR stores much data about each event and by the use of event codes it is possible to follow up events and e.g. see which actions that have been carried out by the users of the train in connection to the events.

It is described by the specialist that other large obstacles when performing follow-up and improving design of future projects is insufficient time and reluctance from the project management to provide funding for such work. Since they work in projects and not directly in the line organization, there is no interest for the project itself to put time and money into follow-up that will not have a positive impact on their own project. Each project is followed up based on its budget and evaluated based on that. This has an impact on which issues the project management puts in focus.
5.4 Design improvements

A desire that is brought up by the manager is that they have to become better at examining the design with help from field data. At the moment, he means that the available field data is not used sufficiently concerning this aspect. To improve themselves within this area they need to become more involved in the design process and have support for their suggestions by using relevant data from the field reports. In some projects the FRACAS process is used, but that is mainly when there are reliability commitments with high demands, the manager explains. Since FRACAS is a quite large and resource demanding process it is not regarded as possible to use it in all projects however, and a more simple and less time consuming process is required.

When it has been clarified that a design change may be necessary, a Modification Request (MR) is initiated of a member within the project team, according to a RAM/LCC engineer. The MR is reviewed by project team members and other specialists. When these persons have elaborated a modification of the design, the MR is distributed to the project management. At a formal meeting, it is decided whether the MR should be implemented or not or if further analysis is required. If it is decided to proceed with the change, the MR is transformed into an Engineering Request (ER), which e.g. contains routines for keeping track of which train units that have been modified.

In case of desired design changes, the suppliers of the equipment mainly do the actual development of the products or sub-systems after BT has placed demands on how the products should be designed, according to the specialist. He means that the cost-effectiveness of the design is affected by the maintenance agreement. If BT perform the maintenance themselves, it is preferable if the trains are easily maintainable. In case the customer handles the maintenance this is of course also important but since BT will not benefit from a design change in this matter it would be up to the customer and BT to agree on the commercial aspects of a design change.

Design reviews are performed in all projects at BT, and the general procedure for these was described by a RAM/LCC engineer. The RAM/LCC department is involved in the internal design reviews. Parallel to these, the system engineers (who are responsible for specific systems) have meetings with the suppliers and with the customer. During the project development there are different design review phases. First, the conceptual design review is held, followed by the preliminary and, in the end, the detailed/final review. They all include descriptions of the systems and technical requirements but in a more detailed extent over time. The design is already broadly outlined before the reviews are held which makes it hard to do considerable changes. The meetings are rather formal and most problems have already been handled among concerned persons before the reviews. Instead, the reviews represent more of a summary of what has been done, bringing the process to a conclusion. The document that is compiled has to be examined and approved by three persons at different functions.

Participants in general at design reviews are;

- System engineers for the most critical systems
- Technical project manager
- Train control management system (TCMS) engineer
- RAM/LCC engineer
- Safety engineer
- Vehicle integrators (electrical and mechanical)
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- Electro-magnetic compatibility engineer
- Manager of system engineers

The RAM/LCC employees are focusing on the contractual demands within their area of interest and strive for achieving these. They have meetings outside of the design reviews together with system engineers, and sometimes the suppliers, to discuss specific parts of the design that is related to RAM/LCC.

EBoK (Engineering Books of Knowledge) is a tool that is used for feedback about e.g. design. It includes a lot of information, such as process information and requirements specification that is used at BT. The tool allows sharing of experiences within the company. All personnel can access EBoK on the Web and some authorized persons can make changes and add new information. In EBoK, it is e.g. possible to find information about experiences from existing and ongoing projects in the form of lessons learned.
6 Analysis
In this chapter, the Design Improvement Cycle (DIC) developed in chapter 4 will be implemented at the case company to test the usability when evaluating the C20 project. Step-by-step, the DIC will be gone through. The information that forms the basis for this chapter can be found in chapter 4 and 5. Since the last parts of the model only can be tested theoretically, these steps have been discussed during semi-structured interviews with personnel that have profound knowledge within that area. The interviewed persons are a team leader for TCMS, software and tools, a vehicle and concept design manager and a project engineering manager. The interview template can be found in Appendix 2. During the interviews, reflections on how BT work with these issues and how they could make improvements in relation to the Design Improvement Cycle were made and these will also be accounted for. A RAM/LCC engineer has also added his opinions on certain aspects.

As a general summary of the reception and testing of the model, the interviewed persons believed that the Design Improvement Cycle was a good working procedure that should be used at the company. They thought that using the model should generate a well-functioning process of gathering field data to improve product design.

6.1 Step 1 - Define key measures
The key measures had already been defined in this case (see section 4.1). They were identified based on the specific area of study, i.e. new design that improves dependability in a cost-effective way. As the key measures should be adapted to the specific case, it turned out that not all of these measures were necessary for the C20 project. In this case, it was clarified that failure intensity and reliability had the same requirements, making only one of them necessary to bring up in the following analysis. Neither was there any need to evaluate if the failure intensity was increasing or decreasing since it was expressed that the only desire was to live up to the required failure intensity and if that is fulfilled this measure is useless. There were no availability requirements in the contract, which made that measure pointless as well. The key measures that will not be treated in the future are marked in grey in Table 6:1.

<table>
<thead>
<tr>
<th>Key measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure intensity</td>
</tr>
<tr>
<td>Evaluation if failure intensity is increasing or decreasing</td>
</tr>
<tr>
<td>Reliability</td>
</tr>
<tr>
<td>Availability</td>
</tr>
<tr>
<td>Maintainability</td>
</tr>
<tr>
<td>Most common failure causes</td>
</tr>
<tr>
<td>Downtime due to substandard acts</td>
</tr>
</tbody>
</table>

*Table 6:1 – Key measures*

To connect the key measures to the specific company measures, it had to be regarded that BT measure failures in terms of failures per million kilometers and that the measures are not standardized, but specific to each project. The maintenance strategy which may be regarded when evaluating cost-effectiveness was not known in this case since the maintenance is performed by an external actor. Therefore it was not known if the repairs made the systems same-as-new or bad-as-old etc. and this aspect was not considered further.
6.2 Step 2 - Identify requirements and criteria for success of key measures

In Table 6:2, the requirements for each key measure are presented. Some of the requirements originate from the contract between the customer and BT, described in chapter 5, while others have been accounted for by a RAM/LCC engineer. All of the requirements are non-functional, i.e. they are connected to external constraints about the overall performance of the system.

<table>
<thead>
<tr>
<th>Key measures</th>
<th>Requirements/Criteria for success</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure intensity</td>
<td>Stoppage in traffic &gt; 10 min: ≤ X,XX FPMK</td>
</tr>
<tr>
<td></td>
<td>Taken out of traffic, train exchange or stoppage &gt; 10 min: ≤ XX,XX FPMK</td>
</tr>
<tr>
<td></td>
<td>Total failure intensity: ≤ XXX FPMK</td>
</tr>
<tr>
<td></td>
<td>The requirement is to comply with the contractual failure intensity but this measure can also be used to show the most important improvement objects.</td>
</tr>
<tr>
<td>Maintainability</td>
<td>MTTR: ≤ X,X hours</td>
</tr>
<tr>
<td></td>
<td>XX% of all failures should be remedied within an hour</td>
</tr>
<tr>
<td></td>
<td>Time to repair a single fault: ≤ X hours</td>
</tr>
<tr>
<td></td>
<td>Regarding these measures it should be noted that it is mentioned in the contract that they “should” (not “shall”) be fulfilled.</td>
</tr>
<tr>
<td>Most common failure causes</td>
<td>To find the root cause of the most frequent and severe failures (according to failure categories).</td>
</tr>
<tr>
<td>Downtime due to substandard acts</td>
<td>Finding downtime due to failures that are caused by e.g. misuse or dissatisfying performance of the service personnel.</td>
</tr>
</tbody>
</table>

Table 6:2 Requirements/Criteria for success of key measures

6.3 Step 3 - Collect and select relevant field data

The upcoming step analysis, i.e. finding the key measures, was the primary aim of the data collection and selection. Unfortunately, there was no possibility to use complementing data sources, which was recommended in the model. To collect the necessary field data from PREMAX, the data was filtered to make sure that only the failure reports for the C20 project were shown. Then, a defined time interval was set, assuring that the data originated from between 2003-01-01 and 2005-10-04. This timeframe was set partly to avoid systematic failures which can be common in the beginning of a project. That made it interesting to disregard the failures from the first years. The final date signified the last warranty failure for the train units. When these filters had been set, the data was exported from PREMAX to Excel.

To find the data that was necessary for finding the key measures that were identified as being important in step 1, the table created in section 4.1 (Table 4:2) was used, only deleting the key measures that were not needed in this project, see Table 6:3.
### General data need in field reports

<table>
<thead>
<tr>
<th></th>
<th>Key measures</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Failure intensity</td>
<td>Maintainability</td>
<td>Most common failure causes</td>
<td>Downtime due to substandard acts</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Description of fault</th>
<th>Failure consequence/category</th>
<th>Operating conditions</th>
<th>Comments</th>
<th>Time to complete service</th>
<th>Type of inspection</th>
<th>Maintenance action/rectification</th>
<th>Equipment used</th>
<th>Spares used</th>
<th>Time in use before failure</th>
<th>Root cause of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report no.</td>
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<td>failed product</td>
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<td>failed system</td>
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<td>Symptoms of failure</td>
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<td>Maintenance action/</td>
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<td>Equipment used</td>
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<td>Spares used</td>
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<td>Time in use before</td>
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<td>Root cause of failure</td>
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</tbody>
</table>

#### Table 6:3 – Data need for the C20 key measures

The compulsory data was believed to have 4 x’s, the highly desirable to have 2 x’s or more and the desirable to have at least one x. This left us with the following data need for this project (see Table 6:4);

### Field data needed for dependability related design improvements of C20

<table>
<thead>
<tr>
<th></th>
<th>Available</th>
<th>Partially available</th>
<th>Not available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compulsory data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identification of failed product</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time of occurrence of failure</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identification of failed system</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identification of failed component</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highly desirable data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description of fault</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Failure consequence/category</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating conditions</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comments</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to complete service/inspection/fault finding</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Analysis

<table>
<thead>
<tr>
<th>Maintenance action/rectification</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root cause of failure</td>
<td>X</td>
</tr>
</tbody>
</table>

*Table 6:4 - Data on C20 available in PREMAX*

Not all data that was defined as necessary was found, see *Table 6:4* above. The most important, i.e. compulsory, data was mainly available. Just partially available was the identification of failed component though, since the system codes only uses two levels to define what has failed, see *Figure 5:2*. In some cases it was stated in the failure description which specific component that had failed, but not at all times. With the available field data it was possible to find most key measures but the failure causes may not be completely defined since the operating conditions, which can have an impact on the failure causes, were unavailable. It was mentioned in chapter 4 that it may be hard for the maintenance personnel to define root causes of failure and this measure was only partially available. It was mentioned in some reports but far from all. The table above does not represent the whole truth though, since the data only was available or partially available if it had been entered into the field data reports correctly, and that was not always the case. As the Excel file was gone through the data that was believed to be unnecessary, based on the data need defined in *Table 6:4*, was removed and the remaining field data was sorted according to systems/sub-systems and failure categories.

Only the warranty failures were to be investigated since those are the failures that affect BT, causing every failure that was not a warranty failure to be removed. This could easily be done since it is mentioned in each failure report whether it is a warranty failure or not (there were both warranty and non-warranty failures from C20 in PREMAX). All trains where the warranty period had expired before the investigation period started were removed, along with all failures that had been reported when the meter reading was more than 150 000 km since that too means that the warranty period is over. When no meter reading was given, it was investigated if the train unit was in warranty at that time with help from other documents at the company. This was done to make deletion possible of all units where warranty had expired. Reports with no given train unit were also removed. In this way the data were briefly cleaned and prepared to increase the quality and to make it easier to handle and analyze. In total, slightly more than 3000 failure reports remained, waiting to be analyzed. The reports were not gone through one by one, which means that there were possible inaccuracies that could not be investigated during the time at hand. The field data that had been gathered was definitely relevant for the area of study but the accurateness is unclear since the failure reports were not gone through thoroughly.

The use of codes simplified the ability of breaking down the failures on defined systems and, since similar system codes are used on most products, it could enable future comparisons between products in different projects. The system codes made rough sorting of data possible, even though it was discovered that wrong codes had been used in some reports. The data quality could be questioned in many cases since it was not always described which sub-component that has failed or what has been done to amend the failure. The project engineering manager explained that the reason to this might be that the failure reports were created in connection to the occurrence of failure, but the failures were not investigated thoroughly until later and when more information about the failure had been found after some time it became complicated and time consuming to add this information in the previously created failure report. Another complicating issue, mentioned by the project engineering manager, was that there is a risk that failures that are not supposed to be BT’s responsibility are included in PREMAX, e.g. failures due to erroneous maintenance or misuse. The most
basic information could be used to get a good overall picture with help from a rough analysis, though.

The vehicle and concept design manager believed that the company does not reach the subsequent steps in the model with their current working procedure, which means that the present process comes to a halt here.

6.4 Step 4 – Analyze the field data
Here, it was investigated if the products corresponded to the key measure requirements. This should be done by the RAM/LCC department, according to the document “Procedure Design for RAM/LCC”, and the team leader suggested that this should be done approximately monthly for ongoing projects. The vehicle and concept design manager too, upheld that this should be done relatively often and maintained that it has to be done accurately.

The initial step in the analysis was to evaluate the failure intensity. Since the failure intensity is measured in FPMK (Failures Per Million Kilometers) the total distance that the trains had traveled within warranty during the time period in question had to be concluded. Each train unit was taken into consideration, using the distance they had driven at the beginning of the period (if any – some trains had not been delivered at that time) which could be found in data records at the company, and the distance at the end of the warranty. In most cases the distance 150 000 km was reached before the two year limit, which means that this was the end distance measurement. When the distance for all trains in warranty during the studied period had been summarized, the distance turned out to be slightly more than 13 million km. The key measures have been calculated and are presented below (see Table 6:5, 6:8, 6:9, 6:12). External failure categories were used to enable evaluation of the contractual requirements since the internal failure categories do not make sensible comparisons possible.

<table>
<thead>
<tr>
<th>Requirements/Criteria for success</th>
<th>Actual output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stoppage in traffic &gt; 10 min: ≤ X,XX FPMK</td>
<td>X,X FPMK (external failure category 21)</td>
</tr>
<tr>
<td>Taken out of traffic, train exchange or</td>
<td>XX,X FPMK (external failure category 21-22)</td>
</tr>
<tr>
<td>stoppage &gt; 10 min: ≤ XX,XX FPMK</td>
<td></td>
</tr>
<tr>
<td>Total failure intensity: ≤ XXX FPMK</td>
<td>XXX,X FPMK (external failure category 21 – 23)</td>
</tr>
<tr>
<td></td>
<td>In case the “external causes” and “unknown” categories are added: XXX,X FPMK</td>
</tr>
<tr>
<td></td>
<td>(external failure category 11, 21-23, ?)</td>
</tr>
</tbody>
</table>

The requirement is to comply with the contractual failure intensity but this measure can also be used to show the most important improvement objects.

The failure intensity for the carbody greatly exceeds the other systems, indicating that it should be investigated further. It is followed by interiors and control & communication (see below).

Table 6:5 - Failure intensity for the C20 project
With this compilation at hand it could be concluded that all requirements in the contract were fulfilled by a wide margin. The failure distribution according to external failure categories is presented in Figure 6:6.

Based on the available data, it was clear that the Carbody, Interiors and Control & communication are the systems with the highest failure frequencies, indicating that these systems should be focused on. If only the most severe issues are regarded, i.e. failure category 21-22, the same three systems stand out compared to the others, see Figure 6:7. In fact, these systems (37,5% of the systems) together cause 85 % of the total number of failures, which is similar to the Pareto principle, even though the three systems represent a somewhat bigger part of the total amount of systems than what is originally meant in the Pareto principle.
The carbody was regarded as being most important since it had the highest failure intensity. Further examination on the causes for the carbody and interior failures, which are the most failure intense systems, is presented in the “most common failure causes”-part below.

### Maintainability

<table>
<thead>
<tr>
<th>Requirements/Criteria for success</th>
<th>Actual output</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTTR: ( \leq X.X \text{ hours} )</td>
<td>MTTR: ( X.X \text{ hours} ).</td>
</tr>
<tr>
<td>XX % of all failures should be remedied within an hour.</td>
<td>XX % of the failures were remedied within an hour.</td>
</tr>
<tr>
<td>Time to repair a single fault: ( \leq X \text{ hours} )</td>
<td>The time needed to repair a single fault exceeds X hours in 3 % of the cases.</td>
</tr>
</tbody>
</table>

*Table 6:8 - Maintainability for the C20 project*

Maintainability was calculated using the time for all repairs registered in PREMAX, see Table 6:8. To find MTTR, all time (for work hours, trouble shooting and function control) were summarized and divided by the number of failures to find the mean time. MTTR turned out to be very high compared to the contract when this way of action was taken. The figures are misleading though, since the time in the failure reports are not directly comparable to the contractual time. This is probably caused by the fact that time that was not supposed to be included according to the contract, e.g. time for getting spare parts and to perform documentation, actually have been included in the reports, which was mentioned in the empirical findings. Using the time that could be found in the field data reports, it was clear that the actual output was not in accordance with the requirements. Since these requirements were written with the reservation that they “should” be fulfilled, it is not as severe as if “shall” had been written. It would be dubious to draw any conclusions from these measures since it is unclear how the time reporting has been conducted however, but possibly this is an indication that the maintainability should be improved in the future.

### Most common failure causes

<table>
<thead>
<tr>
<th>Requirements/Criteria for success</th>
<th>Actual output</th>
</tr>
</thead>
<tbody>
<tr>
<td>To find the root cause of the most frequent and severe failures (according to failure categories).</td>
<td>The most frequent failures in the failure categories 21 and 22 were studied. When the failure intensity was examined previously it was discovered that the carbody and interiors were most problematic. During further analysis it was concluded that energy should be directed towards exterior doors in the carbody and the interior architecture in interiors and some of their sub-systems.</td>
</tr>
</tbody>
</table>

*Table 6:9 - Most common failure causes for the C20 project*

Even though the contractual requirements are fulfilled, this was investigated to attempt to find the most common failure causes for the systems with the highest failure intensity, see Table 6:9. The system based failure distribution was broken down further to find the sub-systems...
that cause most issues. When the failure data about the carbody, which had the highest failure intensity, had been broken down and compiled it was evident that the exterior doors were most problematic, causing 91.5% of the failures, see Figure 6:10.

![Figure 6:10 - Failures carbody, category 21-22](image)

This level is too wide though, since the exterior doors consist of many sub-systems and components and therefore the problems had to be broken down further to find the root causes of failures. The system codes could not be used to get any further and therefore the texts in the reports had to be studied. During analysis of field data that concerns the exterior doors in failure category 21-22, it could be seen that many failure reports lacked information about which sub-system that was affected. In fact, the failure cause “unknown” was the most frequent one. On second place was the door machinery, closely followed by the DCU (Door Control Unit). In the door machinery, recurrent issues were e.g. the suspension arm and the switch (DCS). Common failure causes in general also turned out to be different adjustment problems. Concerning the DCU the main issues were communication problems between the unit and the TCMS system.

Also the interiors on second place (see Figure 6:6 and 6:7) were examined. After sorting based on the system codes in the failure reports, it could be seen that the interior architecture is most problematic, see Figure 6:11.

![Figure 6:11 – Failures interiors, category 21-22](image)
After studying the failure reports more carefully, it could be seen that about 61% of the failures within the interior architecture category depended on the master controller while the remaining failures were quite evenly distributed among other sub-systems with such low failure intensity that they are not relevant to bring up.

Using the field data was a good way of getting a first insight but during this stage, the Team leader for TCMS emphasized that it would be advantageous if the RAM/LCC engineers and personnel from PI (Product Introduction) could cooperate since PI may have supplementing information if that is regarded as necessary. It was brought up by the vehicle and concept design manager that RAM/LCC engineers are not able to find the root causes themselves merely by the help of field data. Instead the failures have to be discussed within a team of concerned personnel. He believed that this should be done during structured meetings (e.g. design reviews) where system engineers, RAM/LCC engineers and personnel from physical integration should be included.

<table>
<thead>
<tr>
<th>Requirements/Criteria for success</th>
<th>Actual output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding downtime due to failures that are caused by e.g. misuse or dissatisfying performance of the service personnel.</td>
<td>It was identified in the “most common failure causes”-part that adjustment problems were common failure causes for the exterior doors, and this causes downtime.</td>
</tr>
</tbody>
</table>

*Table 6.12 – Downtime due to substandard acts for the C20 project*

Since all requirements according to the contract were fulfilled and this measure requires deep-going and time-consuming analysis, it was not evaluated properly. A common failure cause that was found earlier in this chapter, the adjustment problems in the doors, may be regarded as being caused by substandard acts though, see Table 6.12, and this causes downtime. After discussions with a RAM/LCC engineer it was clarified that adjustment problems can be caused by insufficient maintenance manuals and education. Other influencing factors are likely to be inexperience of the service personnel and a low interest to learn how to do adjustments of the doors, which requires precise handling.

### 6.5 Step 5 – Create reports presenting key measures

The report aimed at explaining the results of the field data analysis, showing the performance regarding the key measures and clearly indicating which objects that are most problematic. It should be written in an easily understood way, to enable everyone involved to understand it and thereby simplify decision-making. An example on what a report could look like in this case is presented in Appendix 3. Also the cost perspective should be included to show the importance of improvements and to increase the understanding for everyone concerned, but those aspects were only touched upon briefly. In the previous evaluation the external failure categories were used to enable comparisons between the actual output and the requirements in the contract. At this report stage however, the internal failure categories are more helpful and should be used since that facilitates comparisons to other projects, which is valuable for the company. In case it is regarded as useful, also the external failure categories may be included. The vehicle and concept design manager mentioned that internal failure categories are useful if they are possible to get hold of, but he meant that comparisons still have to be done.
carefully since it cannot be guaranteed that the failure categories have been used consistently in all projects. If only external failure categories are available (which is the case in some projects) they can be used as well since the most problematic systems can be concluded with help from them too.

It is essential that the problems are broken down as far as possible, identifying the most problematic components. This was emphasized by both the team leader for TCMS, software and tools and the vehicle and concept design manager, during the review of the model. The team leader stated that it is a good idea to use a report at this stage and he, as well as the project engineering manager, meant that it should be sent to the system engineer for exterior doors since he is responsible for the system in question and is required to push the improvement process further. Possibly, the report can be sent to the service personnel in order to make them see the benefits of creating reports and to motivate them in their future failure reporting activities. Sending the reports to the ones performing the maintenance is a very good idea according to the RAM/LCC engineer since that should motivate them and make them see that their reports come to use. It can also be good as a feedback for them to see if they have entered the data correctly or if changes are needed in their reports.

6.6 Step 6 – Evaluate situation/Determine improvement objectives

Based on the analysis and the following report it could be concluded that the carbody with its exterior doors is the main problem area since the failure intensity by far surpasses the other sub-systems. In the exterior doors, the door machinery and the DCU cause many of the failures and therefore it may be investigated if a more cost-effective and more dependable solution for these can be found. In this specific project however, the contractual requirements, i.e. the criteria for success, were fulfilled which means that no change is needed. It would not be cost-effective to make changes on the current design. It can be assumed that the requirements will be tougher in the future but in this project it would actually be a bad choice to do changes since the contractual requirements are fulfilled and the warranty time has expired for all trains. That means that they do not risk any penalty fees and that failures do not cost BT anything. Therefore they would not have any benefit from a change in the design. It would only cost them a lot of money, causing non-cost-effective improvements of dependability, which is the absolute opposite of what is aimed for. Consequently, it would not be cost-effective to improve the design until customer demands on future product generations are known, since it is unnecessary to improve things that do not need to be improved or to make them better than what is required. This means that the Design Improvement Cycle comes to an end here, for this project with the current prerequisites. The following steps will be described in general terms though, just to clarify how they would be conducted in case improvements had been necessary.

Even though it is not necessary for this project it can be useful to know where the biggest improvement possibility lies for future projects. To get the long-term approach, the project engineer manager implied that the improvement ideas should be established in the line organization since the projects are limited in time. To make this work, there has to be an interest to make use of feedback and at the present that interest is somewhat weak. If a change had been needed, an MR (Modification Request) would have been initialized in this phase, according to the team leader and the vehicle and concept design manager.

The team leader and the vehicle and concept design manager highlighted the importance of finding the root causes of the failures at this stage, in case improvements had been regarded as
necessary. In order to find these, the field data analysis may have to be complemented with data from EDGAR. Also the project engineering manager pointed out that the root causes are extremely important to identify and mean that e.g. the surroundings must be analyzed. Other solutions to finding the root cause could be to install equipment that performs measurements on a number of train units. He meant that own measurements are especially important when the failures are complicated. The team leader also emphasized that it would be positive if the RAM/LCC personnel, during this stage, could assist the system engineer to highlight the most important components. In case they could participate in discussions with the suppliers that would be good as well.

6.7 Step 7 – Choose most cost-effective improvement object

In case improvements had been found necessary in the previous phase, the most important one would have been pointed at in this stage, showing how much the company could gain by making the dependability improvement. E.g. aspects in the contractual LCC commitment between BT and the customer could guide which costs that should be included, e.g. annual maintenance cost, corrective and preventive maintenance cost, kilometer dependent maintenance and inspections, as well as operational cost and possible penalty costs for not fulfilling the dependability requirements. The reason for the improvement would presumably be the financial savings and these could have been supported by analyzing the failures and their influence on the equipment and maintenance. Estimations of the financial output, i.e. the cost-effectiveness, of a new solution would be supported with help from relevant data. As a suggestion, if the trains had still been in warranty causing many expensive repairs or if the requirements in the contract had been tougher, it should have been investigated if a better and more cost-effective solution of door machinery could be found. A design review could preferably be conducted during this step, according to the team leader, and in case something would have to be attended to, the responsibility would lie on the system engineer to take the procedure further. The vehicle and concept design manager explained that the failure consequence has a big impact on which failures that are focused on and clarified that issues concerning safety has the highest priority, followed by financial consequences for ongoing projects, and lastly long-term technical improvements and financial consequences for future projects. Also the project engineering manager believed that the safety issues are most important but he emphasized that they are discovered earlier and therefore it is unlikely that they are detected during field data analysis. Nevertheless, hardly any system development is performed before a new customer contract is secured.

During this step, the team leader proposed that a thorough evaluation should be done, which could lead to a suggestion on a solution. The project engineering manager mentioned that the suggested improvement does not necessarily have to be a change of the actual door design, the root cause of the failures might as well be in the surrounding systems. If it would be decided to make a change, an Engineering Release (ER) would be created here. To make a deep-going analysis, EBoK could have been used to search for previous experiences within the exterior door area.

After this step, it would not have been possible to test the model, even in case a necessary design improvement had been discovered, since the design process is complex and very time consuming. The conduct of the following steps, assuming that new design would have been found necessary, will be described (and tested) briefly, however, with help from the interviewed persons at the case company.
6.8 Step 8 - Develop/Update new design

Here, the engineers would attempt to find a better design that would fulfill the requirements and be more cost-effective than the previous one. The improvements would be inspired by the improvement objects defined in previous step, i.e. improving the dependability of the door machinery and techniques such as FTA, RBD, FMEA or HAZOP could have been used as an aid in the process. However, as far as the team leader knew, these tools are not used by the engineers. He believed that RAM/LCC and safety personnel are the only ones that make use of these tools. Since this is the case, the team leader proposed that it would be useful if the RAM/LCC and safety engineers would work together with the engineers concerning these aspects. In case the sub-system/component in question is delivered from a supplier, the requirements should be forwarded to the supplier to enable improvements of the delivered products. Different functions within the company (and possibly the suppliers) should work together to find the most optimal design, possibly in connection to design reviews during the different phases of the design update. The vehicle and concept design manager meant that several design reviews can be held during this and the following step. In the design reviews it should be investigated if the performance requirements will be achieved and discussion on how to solve potential problems should be held. The system engineer should be responsible for pushing on the design improvement process for his system, according to the team leader.

The most suitable solution is found in discussions in the project. The solution is dependent on the suppliers of the equipment as well, and therefore they must be considered. In the best case scenario the suppliers and BT could work together to find a solution, the team leader suggested. According to the vehicle and concept design manager the system engineer is responsible for handling this issue together with the suppliers.

Advantageously, possible changes should be done as early as possible to reduce the cost of the design procedure and it is necessary that the reliability engineers are included in the evaluation. This in line with the “Procedure, Design for RAM/LCC” document that implies that the RAM/LCC department should evaluate design suggestions from engineering based on the RAM/LCC requirements.

6.9 Step 9 - Analyze new design

When a suggestion on new design of the door machinery has been developed it needs to be overhauled with respect to key measures and cost-effectiveness. In case of several suggestions, the most suitable one should be chosen. The change is dependent on the requirements from the customer and the solution that is regarded as the best one, not necessarily the cheapest, is focused on, according to the team leader. It is essential to assure that the key measure goals are met with the new design, and this can be done during the several design reviews that the vehicle and concept design manager believed should be held at this stage of the Design Improvement Cycle. As far as possible, the new design should be tested, according to the vehicle and concept design manager and the project engineering manager. It can be tested extensively in the lab or by test montage in order to verify the dependability prior to installing the doors in a train, the team leader proposes. The scope of the testing would of course depend upon what and how much that was modified and how complex the modifications were.
6.10 Step 10 - Implement the solution
In the implementation phase the new door machinery would be installed on the fleet and used in its true environment, in a train unit driving in normal traffic, hopefully performing as intended. To evaluate the performance, different functions within the company, such as RAM/LCC, PI and the system engineer should be involved and proper documentation should be created describing how the new design is functioning. The team leader emphasized the importance of having high quality documentation.

6.11 Step 11 - Estimate success of solution
After the new door machinery has been in use for some time the performance must be evaluated. If the design was regarded as successful, the solution should be standardized and spread within the company. If it was unsuccessful with regards to the key measures and the cost-effectiveness, an even better design has to be found.

This follow-up is not performed to the extent that is desired at BT currently, according to the team leader. In this step, field data, possibly complemented with data from EDGAR, could be used. A wish from the team leader was that the RAM/LCC engineers would actively perform the follow-up.

6.12 Step 12 - Store the solution for future reference
Regardless of the performance of the new design, the solution has to be stored in order to either promote or prevent a similar design in the future. If the new door machinery was successful, it should be easy to find detailed information about the design and the entire improvement process. In case of poor results it should be simple to find documentation to avoid making the same mistakes again. If the results were dissatisfying the cycle has to be repeated from step 8, developing new design suggestions again. Supposing that this solution was successful but more improvements would have been necessary to reach the requirements, the DIC would be performed an additional lap, focusing on the second most important issue.

This final step could be realized by using EBoK (Engineering Books of Knowledge) and providing lessons learned from the performed process. At the present the team leader, the vehicle and concept design manager and the project engineering manager mean that this tool is not used satisfactory, and this is something that BT need to become better at. They must work in a more structured way with follow-up and give it a higher priority. The team leader implied that the technical project manager should control this. According to the vehicle and concept design manager a simple search engine is needed in EBoK that enables searches that are independent of projects and instead dependent on systems. The text must also be reduced since the amount of text that appears currently is too extensive which makes it very time-consuming to use EBoK. Problems also arise since there is no agreement on how and which information that should be stored. Since this step usually is performed very poorly, the Design Improvement Cycle is not closed at the company.
Results

In this chapter, the main results that were discovered during testing of the Design Improvement Cycle in the analysis are presented. The achievements during each step will be accounted for and the model and its applicability will be discussed.

7.1 Achievements step-by-step

During Step 1 – Define key measures, the key measures for dependability related design improvements were presented, based on theory. These were then narrowed down to suit the project in question since some of the measures turned out to be irrelevant for the C20 project. Therefore those measures were left behind.

In Step 2 – Identify requirements and criteria for success of key measures, the requirement for each remaining key measure was identified with help from the contract and an engineer.

Step 3 – Collect and select relevant data, contained the actual data gathering. To find the output in the C20 project regarding the key measures, data from failure reports in PREMAX were exported to Excel. The data in the Excel file were then briefly cleaned (by e.g. removing all failures that were not regarded as warranty failures) and sorted. Thereafter the data that were believed to be necessary in order to facilitate evaluation of the key measures were identified and the unnecessary data were deleted. In many cases the data quality was questionable, partly since the reports were not detailed enough which made it hard, or even impossible, to define the failed component. However the most important, compulsory, data was mainly available.

During Step 4 – Analyze the field data, the key measures were calculated/evaluated and compared to the requirements. The system codes and the external failure categories enabled rough evaluation of the failure intensity and indicated the most problematic systems and sub-systems. It was made clear that the carbody and interiors had the highest failure intensity and therefore these issues were chosen for further analysis and should be focused on primarily in case of improvement requirements. It could be concluded though, that the key measure goals were met. The maintainability turned out to be hard to evaluate, probably since the time that was entered into PREMAX was not in accordance with the time specified in the contract. If the time in PREMAX was correct however, the maintainability may be an issue to look further into, even though it was only stated that the requirements “should”, not “shall”, be fulfilled, making possible deviations less important. To further break down the problems, the failure reports for the most failure intense systems in the most severe failure categories were gone through as an attempt to find the most common failure causes, and the most critical components. For the carbody, the exterior doors caused nearly all of the failures and it could be concluded that the causes of most failures were “unknown”, followed by problems with the door machinery and the DCU. Common causes of failures were also different adjustment problems. Concerning the interiors, the interior architecture and more specifically the master controller was most problematic. The substandard act-related downtime analysis was not performed in a thorough sense, but the adjustment problems for the doors were brought up as an issue. Besides from the maintainability calculations, the results were good compared to the requirements and seemed reliable. To enable better analysis in the future, some improvement suggestions emerged during the interviews. It would be positive if RAM/LCC engineers could cooperate with PI, system engineers and others to get deeper knowledge about the problems. However, an analysis similar to this one can be used as an initial indication on where the efforts should be put.
Step 5 – Create reports presenting key measures included the report which summarized everything that was important in order to present it to the concerned personnel, primarily to the system engineer. It was supposed to function as a support in the decision-making and in this case the report was aimed at the problems with the exterior doors since they had the highest failure intensity. A desire to send the report as feedback to the service personnel was also expressed.

As the situation was being evaluated in Step 6 – Evaluate situation/Determine improvement objectives, it was determined that no cost-effective improvements could be done on the C20 project since the requirements were already complied with and the warranty time had expired. The Design Improvement Cycle thereby came to an end here for this specific project since no improvements were necessary. Given that future product generations are considered however, it is possible, or even likely, that the requirements will be tougher. In that case, the systems that have been defined as problematic should be attempted to improve first, since improvements there will have a big impact on the overall dependability and cost-effectiveness. In order to make this work and to get the long-term approach, this feedback should be established in the line organization. If it had been determined that changes were required, a deeper investigation of the problems would have been performed here and an MR would have been initiated.

By the use of the DIC it was made clear that the C20 project is not in need of any design improvements at this moment. That conclusion caused the model to come to a halt after step 6 but the upcoming steps of the model were discussed in the analysis in order to have some kind of reasoning in connection to them and to evaluate if they are sensible. According to the interviewed persons the final steps (Step 7 – Choose most cost-effective improvement object, Step 8 – Develop/Update new design, Step 9 – Analyze new design, Step 10 – Implement the solution, Step 11 – Estimate success of solution and Step 12 – Store the solution for future reference) were good and should be aimed at following. In the matter of developing new product generations, assuming that the requirements from the customers will be tougher, this model gives the impression of being suitable and it gives a good possibility of finding the most important objects for design changes and spreading the information to concerned personnel.

7.2 General reflections
One big restraining issue when carrying through this model was the data quality in the field reports since many of the reports declared unknown failures and others were hard to interpret. An aspect that may have lowered the reliability in the analysis of field data was that the reports were not overhauled carefully, which means that they were not cleaned to the extent that may have been needed due to incorrectness and other issues. However, since the analysis was performed in a somewhat rough sense, meaning that the details were not considered being highly important, focusing on getting a bigger view on which systems that were most problematic instead, this should not be a big problem. The rough failure distribution was used as an indication on which systems that should be studied more carefully, and the field data reports for the most severe failure categories for these systems were gone through one by one. It would have been preferable if the failed components had been clarified in a better way, though. If further analysis and design improvements had been necessary, the evaluation in the analysis chapter would not have been sufficient and other functions or data sources at the company would have to be involved.
Identifying the data need for dependability evaluation made it possible to clarify insufficiencies in the field data reports. In the studied case, it could e.g. be observed that the absence of data that identified the failed component lowered the quality of the analysis. When testing the model, it was discovered that field data exclusively was not sufficient. It could be used for initial analysis and indicate which areas that should be focused on, but if design should be modified the field data must be supported with information from other sources. In the model it was brought up that the field data preferably should be complemented with other data and if that had been done the analysis could have had a higher quality.

Another aspect that can be considered is the contractual requirements from the old project that have been used as criteria for success in the analysis and evaluation. Perhaps those criteria for success are not tough enough since new product generations should be better than the old ones? A problem occurs however as the company only wishes to fulfill customer requirements, and not necessarily to exceed them. Therefore they are not interested in changing things unless they have a defined requirement from a customer that has to be met, which is reasonable from a cost-effective point of view.

During the testing, it was concluded that the developed model was practicable and that it was a working procedure that should be aimed at, according to personnel with competence within the subject. By comparing the current working procedure for field data follow-up and design improvements at the case company to the DIC, weaknesses at the company could be revealed. It was indicated that the current working procedure regarding these issues at BT does not resemble the developed model to a big extent, showing several shortages. Follow-up of field data is not performed in a structured sense with the objective of making improvements in product design and it was indicated that the interest of assimilating feedback was relatively poor. The last step of the DIC had a big improvement potential at the company, since the storing and utilization of previously gained experiences was criticized by the personnel.
8 Conclusions
This section aims at answering the problem formulation which was developed in the introduction chapter. The model will also be evaluated, treating positive and negative aspects as well as reliability, validity, and generalization.

8.1 Answer to the problem formulation
As the first part of this conclusion chapter, the problem formulation will be treated;

 ✓ Which field data are needed and how should these be assured and utilized in order to support cost-effective design improvements of existing and new product generations, with respect to dependability?

The field data need was defined using a top-down analysis. First the desired key measures for evaluating dependability were found. Then the common data need in field reports was used to define which data that were needed to evaluate the key measures. The data that was regarded as applicable were divided into classes based on importance; Compulsory, Highly desirable and Desirable. The most important field data, i.e. compulsory, turned out to be “Identification of failed product”, “Time of occurrence of failure”, “Identification of failed system”, “Identification of failed component” and “Failure consequence/category”. For the remaining data need, see chapter 4, Table 4:3. Using exactly this data is not an absolute requirement though. Instead this should be regarded as a guideline. To find the data need for other areas of study the same procedure as the one used here can be carried out. Even if the same area, i.e. dependability related improvements, is studied the data need can be adjusted in case not all key measures will be used.

To find a way of assuring and utilizing field data in order to make cost-effective design improvements related to dependability, a working procedure called the Design Improvement Cycle (DIC), was developed. It is a 12 step model that can be seen as a continuous improvement cycle. By the use of the model, the field data can support design improvements of existing and new product generations. Making decisions that will benefit the company in a cost-conscious way was regarded throughout the model. Identifying the field data that is needed to achieve this is included as a part of the DIC.

8.2 Evaluation of the model
The DIC was developed by compiling existing theories into a model that appeared to signify an appropriate working procedure for design improvements related to dependability with help from field data. It presents a view on how the field data can be used concerning these matters. To make sure that the model was useful and realistic, it was tested at a case company, with good results. A positive aspect with the DIC is that it considers the cost-effectiveness. Due to that, it is made sure that only relevant improvements are done, i.e. the ones that actually are profitable for the company. There is no need to improve design if it will not lead to any benefits. Another positive feature is that the model is very flexible, which actually means that it does not have to be used with field data and it can be used for other purposes than improving dependability related design. The only action that has to be taken is to change the key measures and the data need in order to make it work. The DIC should be possible to use for many producing companies as a way to improve their products and since the model supports continuous improvements and feedback of experiences it should help companies to compete on the global market.
A restriction that was discovered during the testing of the Design Improvement Cycle was that merely field data gave the impression of being insufficient for design changes. It has to be considered that other information sources most likely have to complement the field data in order to perform an analysis that is detailed enough to detect the root causes of failures and thereby show where the improvements actually are needed. That aspect should perhaps have been given more attention in the model since it was just briefly mentioned. However, the field data is the best way of finding actual performance, in spite of possible data quality issues, and therefore it is useful for follow-up. The field data need that was defined for dependability related evaluation in the model can be questioned since it is based on subjective judgment. As a saving clause it has been mentioned that the data need should be adjusted to the specific case. The procedure when finding the necessary data can be used as an inspiration if this data need is not regarded as suitable.

To evaluate if the study is reliable it has to be estimated if the research could have been redone at another time and still give the same results. Since the model was created based on existing theories, it should have roughly the same appearance even if it had been created at another time or by another researcher. However, in order to create a logical, and useful model, some own assumptions and clarifications had to be made by the researcher, which may have lowered the reliability. Nevertheless, all theories, assumptions and data collection methods have been presented clearly in the thesis. Several data gathering methods have been used at the case company to increase the reliability, such as observations, interviews and quantitative data analysis. To make sure that the right things have been investigated, i.e. that the internal reliability is high, the supervisors have given their opinions on the thesis. The external reliability which signifies the possibility of drawing general conclusions is relatively high since the model is based in general theories, and the case company was only used to test if the model was usable. To make sure that it is clear which aspects that may have been affected by the case company in the analysis, the company prerequisites were described thoroughly, which makes it possible for the reader to evaluate if the model is useful in the surroundings where he/she operates.
9 Recommendations

In this final part, recommendations for the case company are given based on achievements in the previous chapters, as well as suggestions on future research within the area of study.

9.1 Recommendations for the case company

It is believed that the case company would profit from having a more structured way of utilizing field data, and having the future in mind during follow-up. To make that work, the Design Improvements Cycle can be used. Primarily, there has to be an interest within the organization to assimilate performance data and to make use of past experiences from other projects, e.g. via EBoK. Since the personnel indicated that the tool is not used sufficiently, it may have to be investigated if there are ways of simplifying the use of EBoK in order to make the tool more attractive. As the project organizations are limited in time, the improvement suggestions should be established in the line organization to get the long-term view.

The analysis showed that some field data that is very important in order to facilitate good quality follow-up is lacking. The main issue is that it is not clarified in PREMAX which component that has failed, at least not in most cases. That makes a detailed follow-up hard, or impossible, to perform with help from field data. If the system codes were broken down to include at least one more level, or if it was written in a better way in the failure description which part that had failed, it would be easier to locate the most severe issues. To make that work, however, it is crucial that the reports are filled out correctly. One possibility to increase the quality of the reports may be to review them before they are entered into the system. E.g. the maintenance manager could look into the reports to assure that they live up to the requirements. Education for the service personnel on how to fill out the reports and to clarify the importance of high quality data might be helpful as well as feedback from the departments utilizing the field data (for instance RAM/LCC and Product Introduction), which could increase knowledge and motivation. Anyhow, there will probably be a risk that the service personnel is unaware of which part within a specific sub-system that has failed immediately after the occurrence of failure, and in such case that information should be entered later on if it is detected.

In general, a good cooperation between the personnel at different functions, such as RAM/LCC engineers, Product Introduction personnel, Service personnel and System engineers would be useful in the continuous improvement process of finding root causes of failures and developing ways of excluding them in future designs.

9.2 Future research

The DIC has only been tested in a single case study and therefore other case studies should be performed to confirm the usefulness of the model. To fully validate the Design Improvement Cycle, it would be necessary to follow the whole cycle, one or several times, to get a comprehensive picture of the effectiveness of the model and to estimate the success of the procedure. In such case, it would be required to study a project or product that is in the need of improvements.

Concerning the subject of connecting field data analysis to a continuous improvement process, there is room for plenty of more research. The subject field can be enhanced into including feedback and learning in a wider aspect.
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Westberg, Ulf, Specialist RAM/LCC
### Brief railway dictionary, English-Swedish

<table>
<thead>
<tr>
<th>English</th>
<th>Swedish</th>
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<tbody>
<tr>
<td>Auxiliaries</td>
<td>Hjälpsystem</td>
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<td>Korg</td>
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<td>Framdrivning</td>
</tr>
<tr>
<td>TCMS (Train Control Management System)</td>
<td>Tågdatorsystem</td>
</tr>
<tr>
<td>Ticketing</td>
<td>Biljettutrustning</td>
</tr>
</tbody>
</table>
Appendix 2

Semi-structured interview template for the analysis phase

Go through the model, explain the steps and investigate if the model seems reasonable.

Focus on the last steps (8-12) to get to know how they could have been carried out in this specific case.

- Is it a good idea to write a report based on the field data analysis and to send it to concerned persons?
  - Who should it be sent to?
  - Would it be preferable to have internal or external failure categories in the report?

- How would the most important improvements be chosen? (based on e.g. cost or other aspects)

- Is it positive if the RAM/LCC engineers identify the components that are most important to focus on?

- Would tools like FTA, RBD, FMEA or HAZOP be used during the design phase?

- Which departments would/should be involved during design improvements?

- How often should field data analysis be done?

- At which steps during the design improvement cycle would design reviews and MR/ER’s be suitable?
1. Introduction
This report presents the performance of the C20 project, based on the field data reports in PREMAX. Only the warranty failures have been included in the evaluation. The train units were within warranty for two years or until they had run 150 000 kilometers. This report intends to indicate which failures that are most common and which ones that, possibly, need to be amended in future product generations. It should be noted that the contractual requirements were fulfilled in this project, making changes in the current project irrelevant.

2. Investigated data
For this report, data from 2003-01-01 to 2005-10-04 were studied. This period was chosen to get a large data set to facilitate the first analysis. However, the first years of operation were disregarded to avoid initial systematic failures. The period ended with the last warranty failure report. Some systematic failures, the ones that appeared during the studied period, have been included in the evaluation. In total, slightly more than 3000 failure reports were analyzed.

3. Failure categories
The following internal failure categories have been used in the evaluation, and the three most severe categories have been focused on;

<table>
<thead>
<tr>
<th>Failure category</th>
<th>Failure mode</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Significant</td>
<td>Train removed from service</td>
<td>A failure that prevents train movement or causes service delay greater than 15 minutes.</td>
</tr>
<tr>
<td>20. Major</td>
<td>Service delay and/or critical failure</td>
<td>A failure that must be rectified for the train to achieve its specified performance and/or causes a service delay greater than 3 minutes but not greater than 15 minutes.</td>
</tr>
<tr>
<td>30. Medium</td>
<td>Extra workshop visit</td>
<td>A failure that does not prevent the train to achieve its specified shift/round trip but demands extraordinary corrective action.</td>
</tr>
<tr>
<td>40. Minor</td>
<td>Revenue service not affected</td>
<td>A failure that does not prevent the train to achieve its specified performance. Corrective action to be executed during scheduled maintenance.</td>
</tr>
<tr>
<td>50. Third party</td>
<td>External cause</td>
<td>A failure that appears due to externally related incidents such as; operator’s fault, accident, vandalism or incorrect maintenance.</td>
</tr>
</tbody>
</table>
4. Failure distribution

In the failure distribution statistics it can clearly be seen that the carbody suffers from more failures than the other systems, see Figure 1. Other critical systems are interiors and control and communication.

![Figure 1 – Failures C20 category 10-30](image1)

As carbody failures are most frequent they will be broken down further. By the use of system codes it was clarified that exterior doors cause nearly all failures in the carbody, see Figure 2.

![Figure 2 – Failures carbody category 10-30](image2)
During examination of failure reports (category 10) about exterior doors and steps it was discovered that many reports lack information about which sub-system that was affected. In fact, the failure category “unknown” is the most frequent one. On second place is the door machinery, closely followed by the DCU (Door Control Unit). In the door machinery, recurrent issues are e.g. the suspension arm and the switch (DCS). Common failure causes in general turn out to be different adjustment problems. Concerning the DCU the main issues are communicational problems with the unit. If the root causes to these problems can be terminated, the overall performance will be greatly improved.

5. Cost of failures
For the C20 project, there are no costs related to the failures since the warranty time has expired and therefore it would not be cost-effective to make changes in the design currently.

6. Improvement suggestions
In case there will be a need to develop a better product generation of C20, the first system that should be focused on is exterior doors, more specifically the door machinery and the DCU.