Reliability prediction of complex systems using neural networks
a case study

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Reliability Prediction of Complex Systems Using Neural Networks: A Case Study

by

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Preface

With this document I finish my master thesis project at Philips Healthcare Best and my master Operation Management & Logistics at the Technical University of Eindhoven. This project focuses on the reliability prediction of complex systems. The subject of research was to explore a prediction method for reliability of complex systems. A case study was used for the exploration. The case study has been performed at the business line Cardio Vascular X-ray. The project has been performed at the subdepartment Quality and Reliability Engineering of the faculty Technology Management.

Without the support and guidance of my supervisors I would not have finished this master thesis project successfully. I am very grateful for their support and advice, especially during the last phase of the project. I would like to thank my first supervisor Peter Sonnemans, especially for structuring my approach. I also would like to thank my second supervisor Rob Kusters. His recommendations for the methodological approach and the data analysis have been very helpful.

This master thesis project is in parallel with the promotion research of Aravindan Balasubramanian. I would like to thank him for the many discussions we had about the topic.

Next I want to thank my supervisor at Philips Healthcare, Guillaume Stollman for his insight in and knowledge about the world of reliability engineering. Very helpful have been the people in the business line Cardio Vascular X-ray, since they delivered data to perform the case study and gave insight in the development process.

Finally I would like to thank my family and friends for their support and for all the nice times we had during my study.
Abstract

This report presents a research to reliability predication. It has been performed at Philips Healthcare in Best. A case study was used to answer two general research questions. One is about the factors that influence reliability and the second about possible prediction methods. A neural network is constructed to perform a reliability prediction. The prediction is based on the identified factors and corresponding data. Recommendations are given on the approach and findings of reliability prediction in general and specific about the current case study. Also suggestions are given for further research in the field of reliability engineering.

Keywords: Reliability prediction, Neural Networks
Executive summary

The current report describes the research which is conducted in the master thesis project. The research is based on the reliability prediction problem of complex systems.

Background

Time becomes a more essential part of the development process due to competition, hence companies are forced to focus on time along with quality and reliability of the product. The product development process (PDP) can be accelerated in a more secure way when developers have an indication of the reliability of a complex product in the beginning of a PDP. Changing design in the beginning of a PDP costs only a fraction of performing the same change during production or even when the product is already in the field.

Problem analysis & definition

Knowing, or having an indication about the reliability early in the PDP will have several advantages with respect to cost and time. A prediction method can provide an estimation of the reliability of the concerned product. Reliability prediction methods already were developed in the 1950s (Denson, 1998). However these classical methods like the guidebook which the US Navy developed (MH-217 or MIL-STD-217) are not able to perform a good reliability prediction of nowadays capital goods. The classical methods can not use factors that influence reliability during the PDP. The classical reliability prediction methods need to be modernized to further improve the ability of companies to accelerate their production development process. The main problem examined in this project is that it is not clear how to predict reliability of complex products. The method that is chosen should be able to use factors that influence reliability during the PDP.

Research

Therefore the research performed in this master thesis project is about identifying the factors that influence reliability of professional systems and finding a prediction method that can handle these factors to predict reliability.

Case study

Researcher Robert K. Yin defines the case study research method as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used (Yin, 1984). The Angio Diagnost 7 (or short AD7) Patient Table, developed and manufactured by Philips Healthcare, is a professional complex sub system of the Allura Xper imaging system of the Philips Healthcare’s business line of Cardio Vascular X-Ray. This imaging system is used to examine the human body by making images with the use of contrast fluid injected in the patient that can be seen by detectors. The AD7 is a part of the whole imaging system, nevertheless it is found suitable as a subject for the case study since this system is highly complex. The patient table under study is shown in the Figure 1.
Identifying factors

To predict reliability it must be known what influences this reliability during the product development process (PDP). Therefore interviews and a brainstorm session were conducted. There were three main reasons why some of the initial identified factors could not be used for reliability prediction:

- One product: Only the AD7 is investigated, which makes factors that are only variable compared to other systems and constant when comparing with other AD7 tables, useless;
- Unable to Quantify Data: Some factors could not be quantified or were almost impossible to quantify;
- Data unavailability: For some factors no data was available which excludes these factors automatically for reliability prediction.

In the end, six factors remained that were believed to influence reliability. Also reliability indicators were identified from the field. These are shown in the table below.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System Complexity</td>
<td>Scale</td>
<td>levels between 0.4 and 3.0</td>
</tr>
<tr>
<td>2. Hardware version table</td>
<td>Ordinal</td>
<td>1 Original version</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 First adapted version</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Second adapted version</td>
</tr>
<tr>
<td>3. Usage profile</td>
<td>Nominal</td>
<td>1 FD10 2 FD20 3 FD10/10 4 FD10/20 5 FD20/20</td>
</tr>
<tr>
<td>4. Purpose of Use</td>
<td>Nominal</td>
<td>1 Hospital</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 University &amp; Hospital</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Innovation Center</td>
</tr>
<tr>
<td>5. Region</td>
<td>Nominal</td>
<td>1 Europe &amp; Mediterranean</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 North &amp; Sought America</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 Asia &amp; Far east</td>
</tr>
</tbody>
</table>
Data was collected of the factors that were found that were believed of having influence on reliability. This list of factors may not be necessarily applicable to all complex product in general.

**Choosing the prediction method**

When a list of factors with applicable data is available, a prediction method can be chosen on the ground of the criteria that the concerned method can handle the type of factors and the data which is provided with them. Three potential methods to predict the reliability of the AD7 were identified by literature because they could handle factors that influence reliability:

- Multiple Regression Analysis;
- Bayesian Believe Networks;
- Artificial Neural Networks method.

Multiple regression analysis is easy to perform when data is available. Estimating reliability by using this method was tried, also to see whether there was a relative simple relationship between the input and output factors. Base on literature arguments and on the data available, the neural network method (NN) was chosen to perform reliability prediction.

**Reliability prediction**

Because the data available had a very small variance, only 7% of the data was above zero, no relationship was found by using multiple regression analysis. NN is a black box approach a lot of settings can be adapted. Also because of the data problem about the variance and because limited datasets were available, no accurate reliability prediction model could be created.

**Conclusion**

The research came up with a significant long list of factors that were believed to have influence on reliability. Unfortunately only six factors could be used to try to predict reliability. Because the quality and structure of this data was not good enough, no prediction model could be created.

**Recommendation**

In the end, some recommendations are given on collection of more data about the reliability of the AD7 and MTBF values from the field. Also recommendations are given on NN to make an estimation model using two outputs, so when MTBF value is not an option, Call rate and Event code rate could be used at the same time to optimize the reliability prediction model.

Another important recommendation is to keep log data that can support the factors identified. This will prevent a lot of trouble regarding traceability when performing a reliability prediction in the future at Philips Healthcare.
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1. Introduction

In this introduction, first the background of the problem is described, which lead to this master thesis project. The problem analysis in 1.2 introduces the research subject.

1.1. Background

The customer requirements for professional systems (i.e., capital goods) become comprehensive and more complex. To meet those customers’ demands these products become more complex by the advent of numerous technological innovations. Developing complex products is not easy and a lot of testing has to be done to ensure the quality and the reliability of the product or system once it is in the field.

Companies must nowadays not only focus on quality and reliability of the product. Time becomes a more essential part of the development process due to competition. Developing a perfect product will not necessarily mean that the company makes more profit than its competitors. It also depends on the moment a company enters the market. Being the first one at the market will give the company strategic advantages like defining the standard in the product group and determining the price of a product (Lu, 2002). Especially in the last decade this Time-To-Market (TTM) pressure has become very important (Lu et al., 1999). It is important to have a fast product development process (PDP) to be the first one on the market. Companies focusing more on time and costs will deliberately remain upstream problems unsolved. Later on more time and cost might be spent to try to remove theses problems (Lu et al., 1999).

The PDP can be fastened in a more secure way when developers have an indication of the reliability of a complex product in the beginning of a PDP. Changing design in the beginning of a PDP costs only a fraction of performing the same change during production or even when the product is already in the field.

Yates and Beaman (1995) say that 65% (or more) of life cycle costs (see Figure 1-1) are tied up before the end of the concept design phase of product development. This means that at this point in time of the design of the product more than half of the total LCC is fixed.

![Figure 1-1 Over 65% of Life Cycle Cost (Inherent Reliability) is determined by the end of the concept phase of product development (Yates and Beaman, 1995)](image-url)
Reliability of a product is one of the major indicators of the performance of a product or system. The definition of reliability with respect to performance is given by International Electronic Commission (IEC) in their International Electronic Vocabulary, no. 191-02-06 (IEV) as: "The ability of an item to perform a required function under given conditions for a given time interval". Lewis (1996) defines reliability as "the probability that a system will perform its intended function for a specific period of time under a given set of conditions".

1.2. Problem analysis

Knowing, or having an indication about the reliability early in the PDP will have several advantages with respect to cost and time. A prediction method can provide an estimation of the reliability of the concerned product. Reliability prediction methods already were developed in the 1950s (Denson, 1998). However, these classical methods like the guidebook which the US Navy developed (MH-217 or MIL-STD-217) are not able to perform a good reliability prediction of nowadays capital goods. One of the most important reasons is that these methods do not consider the factors that influence the reliability during the development process of the product (Balasubramanian et al., 2008). It is believed (Balasubramanian et al., 2008) that when these factors are used a better prediction of the reliability can be given. So regarding reliability, it is important to be able to use all factors that influence the reliability of the product which is being developed.
2. Research outline

In this section the research outline will be discussed in order to solve the problem indicated by the problem analysis. First the problem definition is stated. From this the research questions are defined. To come to the answer of these research questions an approach is followed which is formulated in section 2.3. Finally in section 2.4 the scope and the preconditions are defined.

2.1. Problem definition

The classical reliability prediction methods need to be modernized to further improve the ability of companies to securely fasten their production development process.

The main problem examined in this project is that it is not clear how to predict reliability of complex products.

Therefore the research performed in this master thesis project is about identifying the factors that influence reliability of professional systems and finding a prediction method that can handle these factors to predict reliability.

Research questions are developed which need to be answered in order to find possible solutions to the reliability prediction problem. In the next section the research questions are given.

2.2. Research Questions

Before being able to perform reliability prediction, or even before being able to choose a method to perform reliability prediction for nowadays complex products, it is necessary to know the factors which influence the reliability. Factors that can influence reliability include the aspects which were used in the classical methods but also can include characteristics of the PDP itself. Before it is possible to choose a method to predict reliability, it is necessary to know all the factors that play a role. When the factors are known, it is possible to indicate the necessary properties of the new prediction method. This leads to the first research question.

What are the factors that can influence reliability of the system?

When all factors that influence reliability are known, it is crucial to have a good prediction method which can handle all the identified factors. Factors can have several forms and properties but the chosen prediction method must be able to work with those properties. This means that the factors that are found play a critical role for selecting a prediction method. This is how we come to the second research question.

How to predict reliability of the system using these influential factors?

Answering these questions, contributes to solving the issues in the reliability engineering field. It is very hard to find a general answer to these questions. A case study is used to try to give grounded answers. The case study has to be performed at a company which can satisfy the demands of delivering a complex product. The results that come out of this research will probably not easily be generalized, but it will give a
better insight in the reliability prediction problem and one step further in solving this problem. The approach for this research is discussed in the following section.

2.3. Approach

In this master thesis project it is tried to answer the research question defined above. In this section the approach to answer these research questions is discussed. To be able to answer the research questions, a case study is used. The approach is ordered in several steps to maintain a clear view of the research. First these steps are listed below and then elaborated.

- Specification phase;
- Identification of factors;
- Data collection;
- Choosing a prediction method;
- Results of analyses;
- Conclusion & recommendations.

Ad 1. The chosen product to perform the case study will be investigated to become familiar with its PDP and properties. The case study is discussed in chapter 3. In order to find the factors that have influence on reliability of the chosen product, people involved in the PDP have to be contacted to provide information. One of the best ways to retrieve information is taking interviews of the involved people. Factors may not only be identified by people who worked on the product, but can also come from literature or outsiders.

Ad 2. When all the sources are investigated, a long list of all factors that are believed to have influence on the reliability of the product is derived. It is important to understand that this long list may include factors that are believed to have influence on reliability but not necessarily have this influence. This list may not be necessarily applicable to all complex product in general. This list of initial factors is given in the first part of chapter 4.

Ad 3. When is known what factors are believed to have influence on reliability data has to be gathered about these factors. There are several types of data nevertheless all data about the identified factors have to be collected to be able to use all of them. It can be that for some kind of reason not all factors can be provided of data. Unfortunately these factors can then not be used for reliability prediction. The remaining factors which will be used for reliability prediction are discussed at the end of chapter 4.

Ad 4. When a list of factors with applicable data is available, a prediction method can be chosen on the ground of the criteria that the concerned method can handle the type of factors and the data which is provided with them. The prediction method(s) chosen will be used to try to predict the reliability of the product or system of the case study. The choice of reliability prediction method is discussed in chapter 5.

Ad 5. The results of the reliability prediction method applied in this case study give a contribution to the general problem of reliability prediction. The analyses and its
results are also discussed in chapter 5. These results of the chosen reliability prediction method(s) will give the answer to research question number two.

Ad 6. In the end the conclusions (chapter 6) will be discussed and recommendations (chapter 7) can be given for further research on this topic.

2.4. Scope and preconditions

The current research concerns factors that have influence on reliability of professional systems. Cost and time are a cause of this subject, but are not under investigation. Furthermore some preconditions are listed below:

- This case study that will be chosen must deliver a complex product that can be used for reliability prediction;
- Interviews will be done to gather information about the product and to identify factors that may have influence on its reliability. People must be available and sympathetic to cooperate;
- Data must be available and useful to support the factors which are identified in order to create a significant model;
- Factors that are identified but are not used for reliability prediction are not further investigated on their behavior of influencing reliability.
3. Case study

The research questions are developed because of increasing interest in the general reliability prediction problem of today’s complex product and systems. The purpose of the case study is to search for answers to the research questions to get a better insight in this problem and to indicate possible solutions. Researcher Robert K. Yin defines the case study research method as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used (Yin, 1984). In this chapter all aspects regarding the case study are discussed. Paragraph 3.1 describes the company where the case study took place and paragraph 3.2 describes the product.

3.1. The company

Philips Healthcare gave the TU/e the opportunity to perform the case study. Philips Healthcare is one of the world leaders in developing and manufacturing healthcare products and it is one of the best performing branches of Royal Philips Electronics. Philips Healthcare develops innovative products in order to satisfy the demand of customers. These innovative products make use of new techniques and often are very complex. Increasing insight in the reliability of a product during the PDP can help developers to improve the quality of the product or system. The contact person at Philips is Guillaume Stollman. He is also the supervisor for this master thesis project. The project is performed at the business unit (BU) Cardio Vascular X-Ray (or short CV). Guillaume Stollman is a reliability engineer in the System Design Group.

Because this research project deals with product development processes of complex systems, it was decided to performing the case study at the CV department by using a complex subsystem. In this way the criteria of investigating a complex product with a PDP which included factors that can influence reliability ware met. The system they provided is a patient table which is actually a subsystem of a whole imaging system. Nevertheless the patient table is a very complex system on its own and is found suitable to perform the research. In the next section the chosen product is discussed more elaborate.

3.2. AD7 Patient Table

This subsystem is the advanced patient table Angio Diagnost 7 or short AD7. The AD7 Patient table is a subsystem of the Allura Xper Imaging system family. This system is used to examine the human body by making images with the use of contrast fluid injected in the patient that can be seen by detectors.

3.2.1. AD7 as subsystem of Allura Xper

The imaging system has several applications. As the name of the development department already reveals, the most two important functions are cardio and vascular. Difference between these two types of investigation is that cardio only concerns the heart area. So a smaller detector (imaging making device) can be used. For vascular scanning a larger detector is used, since a doctor might want to see veins over the entire body width. A bigger detector is also a must to see a larger length of a vein or to compare different veins. Another difference in use of the two utilizations (Cardio /
To give an example, the Pediatric cardio system (Allura Xper FD10/FD20) is an advanced cardiac system providing superior performance for multiple biplane projections. This is good for those procedures where use of contrast medium or examination time is critical.

To get a better idea of what the system is and how the system looks with the detectors, Figure 3-1 gives a nice example. The Xper Allura system shown here possesses a small detector (FD10) ceiling mounted. The AD7 patient table is situated in the lower right corner. Furthermore is shown that the Xper Allura system also includes monitors where the physician the images can see which the detectors picks up. Other equipment which is needed to process all information is not shown in this picture. This equipment is installed in a different room.

As mentioned above, the imaging system has several applications and therefore has the option of having different detectors. The choice of detector depends on the application. There are two sizes of flat detectors (FD), ten inch and twenty inch. Additionally an imaging system can have one (monoplane) or two (biplane) flat detectors, depending on the application. The flat detectors are mounted on a C shaped arm, so that the sent waves from the imaging tube are also received by the detector. The C-arm can be mounted on the ceiling or can be put on the ground (stand imaging). Having two flat detectors gives several advantages like less contrast fluid needed (important for infants) and being more flexible while examining. In the table below, an overview is shown of the different combination of the flat detectors and their suitable applications.

<table>
<thead>
<tr>
<th>Table 3-1 Applications of flat detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardio/Vascular X-Ray</td>
</tr>
<tr>
<td>Cardiology</td>
</tr>
<tr>
<td>Vascular</td>
</tr>
<tr>
<td>Pediatric Cardiology</td>
</tr>
<tr>
<td>Electrophysiology</td>
</tr>
<tr>
<td>Radiology</td>
</tr>
<tr>
<td>Neuro-radiology</td>
</tr>
<tr>
<td>Surgery</td>
</tr>
</tbody>
</table>

Vascular) is that the table for cardio practice does not have to make many special movements, since the heart is always on the same place for every patient. For vascular examination or in case of a surgery, the user wants to be able to put the patient in different angels to have better access to the investigated part of the patient. Giving the physician more freedom of workspace by providing more options like angles and movements will make the examination or surgery easier. This means less exertion for the surgeon, which keeps him concentrated.
As is shown above, the Allura Xper imaging system has several different applications. Due to these applications the AD7 needs to be able to make several required movements. What these movements and functions exactly are will be discussed in the next sections.

3.2.2. Description of AD7 Patient Table

The AD7 patient table is a part or subsystem of the Allura Xper imaging system. Although the AD7 is a subsystem, in this report it is further indicated as product or system. This is done because the AD7 can function on its own and to keep the research manageable. Because of the complex aspect both on the hardware and the software part of the system and the complicated design of the system it is a good subject to perform the case study. At the time the decision was made to use the AD7 for the case study, the system was only in the field for three months. So the PDP did not take place that long ago. This was favorable for the research about the AD7, since the concerned people remember the project reasonably well.

The patient table must be able to take several positions on which the user (doctor, physician or surgeon) needs to examine the patient. That is why the AD7 patient table can be delivered in several configurations. This means that the patient table can vary from rather simple to a complex system with a lot of different motorized movements. The patient table is able to take several positions vertical, horizontal and practically all angles. The extra movements are nice for the surgeon, but make a patient table much more complex. The movements make the AD7 Patient Table to what it is, a complex capital good with a lot of interactions with the overall Allura Xper system. The following picture indicates the movements of the AD7.
As we can see in the picture above the AD7 can move in seven different ways.

- Height
- Longitudinal
- Lateral
- Cradle
- Tilt
- Pivot
- Swivel

To get better inside in the table and its movements, some pictures are shown in the Appendix A. The table can be ordered in 21 different combinations of these seven movements. Height is always included. Some movements require other movements. The combinations of the movements for all 21 configurations are shown in the Appendix B. Because of different combinations of movements, the amount of components and software can vary for all 21 configurations. This is also shown in the Appendix B.

### 3.2.3. Predecessor AD5

The AD7 is the successor of the AD5 and AD6 patient table, where the AD6 is the same as AD5 with only an extra function added (Tilt). In this way the AD7 can be regarded as a derivative product. This meant that probably some concepts and properties of the AD5/6 were used for the development of the AD7. The AD7 has a lot of the same functional properties as the AD5/6. However, the design regarding hardware and software is all renewed. All critical components of the AD7 are different then the AD5/6. Only some general components of the total 3000, like labels and bolts are the same for both patient table types. The software modules are also built up from scratch. This means that new building blocks are built by the software engineers.

Now the subject of the case study is known, the next step of the approach can be made. This means that it should be investigated what factors influence reliability.
4. Identification of Factors using the Case Study

Now the product which is used for the case study is defined, the factors can be identified. First the input factors are defined; these factors are elements and aspects which are believed to have influence on the reliability of the system during the PDP. These input factors will be used as input parameters for the reliability prediction method. The method will be chosen when all criteria are known (chapter 5). Also indicators of reliability in the field will be determined. These reliability indicators will be used as output for the reliability prediction method and they will be discussed in chapter 4.2. When all the factors are known, in section 4.3 an evaluation of the data will be given and some encountered problems will be discussed.

4.1. Defining Input Factors

Prediction reliability requires information about the factors that influence the reliability of the system, which we now know is the AD7 patient table. Factors are all aspects or elements in the PDP, which are believed to have influence on reliability of the product when it is installed in the field. Such factors had to be identified. These factors are the input parameters of the reliability prediction method. Factors that could influence the reliability during the PDP are identified according to a certain methodology. All the steps of defining the factors are discussed in the following sections. First the sources used to gather the factors are explained (4.1.1 literature; 4.1.2 experts’ opinion). 4.1.3 Discusses the factors. Finally 4.1.4 gives an overview of the value of the different factors to use in a prediction method.

4.1.1. Literature

In literature several sources of information are mentioned, and also some factors can be found which can have an impact on the reliability of a system.

Subjective data

There is information from engineers (Cook 1991) who are working in the concerning department and because the products are derivative (not radical) these engineers are familiar with the product line and can be a good source of information. Because these data exists out of experts’ opinion, and is hard to quantify it is subjective data. Because this type of data is hard to quantify, it is also hard to use for a reliability prediction method. Mistakes or wrong interpretations of the data can negatively influence the result of a reliability prediction method, which has to model the reality. However some reliability prediction methods are designed to be able to work with this type of data.

Objective data

The availability of test data, i.e. prototype testing, is an advantage because the department itself determines what they want to investigate. This data is called objective data because no opinions of people are involved, and the data is based on facts. Most of the time, engineers only look to functional (mostly hardware) problems which they have to resolve. Test data of internal usage simulations or small prototypes reflect the actual reliability. These data are collected and when necessary adaptations are made to the system before the product is put on the market. Another form of objective data are software log-files which can be gathered by logging all outcomes.
and steps which a product / system makes while being tested or operated in the field. These log-files can indicate software as well as hardware problems / performance.

**Historical data**

Data which are available from the field of the predecessor product of the currently developed product can be of interest. When these data are stored they can be used as historical data. Because the product is derivative, information and also feedback of the previous product can be useful. Field data (feedback from customers of similar previous products) will bring upfront problems that engineers probably never thought of, e.g. soft failures (Koca et al, 2007). Because the AD7 is new considering hardware design and software design, it is not possible to use the AD5/6 historical data. However, the historical data of the AD5/6 is used during design of the AD7 to prevent typical problems with a patient table.

**Factors that influence reliability**

In literature some general factors are found that can influence reliability of a complex product which is built up out of numerous components and a lot of software.

The complexity of software does often influence the reliability of a system (Lew et al., 1988). The complexity of a program can be assessed in different ways. The most basic metric is to use the size of the program (lines of code or loc). Khoshgoftaar and Munson (1990) found that the size or volume (loc) can be used as relationship to faults in a program. But also the structure of a program is a good metric to indicate complexity. McCabe’s Cyclomatic complexity is such a metric (McCabe, 1976). This metric uses the number of control paths as an indicator of complexity.

Many components in a system do not necessarily lead to a decrease of its reliability. However, the complexity of the system and the complexity of the components can affect the reliability. More components in sequence will influence the reliability then when components are assembled parallel (Lewis, 1996). So the number of components and the way that they are integrated in the system do play a role in the reliability for a system.

**4.1.2. Expert opinion**

To get information about what factors may influence the reliability of the AD7 patient table, it is important to talk to the people who were involved with the development of the product. By interviewing these people it was tried to get an insight to the factors that may influence the AD7.

Because Ph D. students of the TU/e also are working on the subject, some interviews were already conducted with people involved with the AD7. The outcome of these interviews could be used, and lead also to further interviews. Another source of information was a preproduced FMEA (Failure Mode and Effect Analysis) by the hardware architect and his team. This FMEA gave more inside in the importance of some hardware components.

**Interviews**

Gathering information about a specific topic is best done by taking interviews with the involved people (Zimmerman and Muraski, 1995). While there was a clear view about
the aspects needed to be explored, the interviews were semi-structured (Saunders et al., 2000). A list of questions and themes that were to be covered were predetermined, but the interviewees were given the opportunity to talk freely about events and beliefs.

During the orientation phase, it turned out that two departments could have a very big impact on the reliability during the development of the AD7. These departments are the department which designed the hardware part of the AD7 and the department which was concerned with making the software for the AD7. Decision about the design for hardware and software were also made in cooperation with the service innovation department. This department looks from a service point of view (e.g. the service engineer).

The integration of the two major components (hardware and software) of the AD7 involved thorough testing. This was done by the “Integration and testing” department (I&T). Also here it was important to conduct interviews since the testing is important to indicate problems in the design.

After testing the managers will decides whether the design of the product can be taken into production. Before a patient table is delivered to a customer, it is first built up in the OXB (One X-Ray Best) factory at Philips Healthcare to check all functions according to a predefined testing pattern. After this check the table is shipped to the customer. Problems found during these tests are stored in a database called FOREST (FOut REgistratie SysTeem).

People from these crucial departments were interviewed to get their opinions on factors that they believe can influence the reliability of the AD7.

![Figure 4-1 Development departments of the AD7 concerned with reliability](image)

The dotted line in the figure indicates that the service innovation department worked together with hardware and software department. People who dealt with field data were also interviewed in order to get an idea of their opinion about factors that might influence reliability.
Brainstorm session

When it turned out that a lot of factors were found out of these interviews, but that it was not sure that these were all factors, an additional method to find potential influencing factors had to be found. According to Zimmerman (1995) and Saunders et al. (2000) brainstorm sessions are good ways to gather information and gather suggestions relating to the problem. By inviting people from all departments it was tried to get new and unforeseen factors that could influence reliability.

Unfortunately it was not possible to get all invited departments at the brainstorm session. This is a situation which can not be foreseen in a company as Philips. People have own priorities of their projects, this is an important reason why it is hard to find a time that everybody is available at the same time.

The brainstorm session was attended by people from the following departments: Software development, OXB factory and Field Problem analyses. Because only three of the six invited parties were attending, it was decided that every department could tell their own story about reliability of the AD7, starting with the question what they understood by reliability of the patient table. During the session, a discussion emerged about reliability. This was also interesting for the attending people, because they now heard how other departments experience the table and its reliability.

The brainstorm session did not give many new potential factors that can influence reliability, but it gave confirmation about the factors mentioned in the interviews.

The departments which not attended the brainstorm session were interviewed later. During this interview it was tried to mention remarks and opinions of people who did attend the brainstorm session, to create the same situation. The purpose was make the interviewed department can react on this in the same way as they could have done when attending the brainstorm session.

Other interviews

To follow on some leads gathered during the brainstorm session and the initial interviews, more interviews were taken, (sometimes other) departments. In this way it was tried to cover all fields concerning reliability of the AD7. Some examples of these interviews are the Customer service department, Global training delivery department and OXB factory quality managers.

In Appendix C a list of the most important interviews is shown. Also is indicated what factor was indicated by the interview. A summary of the brainstorm session is also given in the appendix.

By interviewing these people and by studying informational documentation about the AD7, a list of potential influencing factors was composed. The order of the following list is arbitrary.

4.1.3. Initial factors

In this section all the factors will be discussed that were found by the methodology described before. The factors discussed in this section are all factors that were believed to have influence on reliability. Per factor is indicated where it was found,
what data was available and why it is thought that it can influence reliability. If possible, it is tried to indicate what the (expected) relationship to reliability is. This is best done when data is already available by using for example linear regression analysis. The order of the following list is not according to importance or the size of the impact on reliability.

**Project management Focus**
The focus of the project can have an impact on the reliability of the product. When the AD7 was developed, management focus was specifically on quality of the product. This was made clear to all departments, because the main focus was building a good product with a high reliability in the field. For example extensive testing was recommended. However when the deadline approached, management shifted the focus on time instead of quality. When time has priority above other elements of the development process, the project will deviate from its original plan. The development process will be adapted to meet the deadline. For example in case the AD7 development for software, this meant that testing of the software didn’t have a priority anymore. The extensive testing which was the original plan could not be done anymore. It is believed that when focus differs from the original plan, more errors will slip trough and can come out in the field.

This factor was indicated by engineers during the brainstorm session. It is hard to quantify, because there is no time pressure level. Also because of the fact that more separate departments were feeling this problem, it is hard to make this factor uniform for all departments involved in the whole project.

**Hardware / Software Interface Integration**
The integration of the interface of hardware and software play an important role in the reliability of the complete system, according to people from the software group. Without a proper connection through the interface, a system will not function properly and errors will occur. Software commands should tell what the hardware has to do, and hardware sensors should tell the software what is going on. Sloppy integration of the interface can result in malfunctioning of the hardware or communication errors in the system.

This factor came up front during the brainstorm session from the software side. But also during several interviews with “Integration & testing”, “software” and “hardware” departments this factor was mentioned. Looking to the design to get an idea of the integration, it is almost impossible to level this factor. Almost every software package has some interaction with some other software package or hardware component. But because it is unknown in what frequency these interactions occur it is impossible to quantify.

**External PC and Operating system**
Software of the AD7 is installed in the computer of the table, but also on host PC outside the system. The reliability of the AD7 depends on the quality of the personal computer and the operating systems (OS) on this PC. The PC as well as its OS is provided by the customer itself and not by Philips Healthcare. Nevertheless, the PC has to comply with requirements demanded by Philips Healthcare.
When the OS platform turns out to be unstable, or when the hardware of the PC can
not withstand the AD7 software or other software installed on this PC, the reliability
of the AD7 will decrease by the influence of the external host PC or its operating
system.

During the brainstorm session the software department mentioned this factor, which is
important. The factor is not immediately considered because it’s an external aspect
regarding the AD7.

**Motion card**

The written software which steers the movements of the patient table is put in a
computer. The motion card provides the actual interface with the moving parts of the
table. This card makes sure that movements and commands to the hardware are
passed on to the right component. This component is most of the time a smartdrive,
which is connected to the actual working motor.

It was indicated by the software department that the quality of this motion card was
crucial for the movements of the table. When the quality of this card is not at the level
it should be it can affect all movements of the AD7.

This part of the design is the same for every individual AD7 patient table. Since there
is no difference between the patient tables, there is also no difference in the motion
card for each system. This makes this factor useless for reliability prediction, because
this factor will be constant.

**Software code**

This factor is compounded out of numerous characteristics of software that can
influence the reliability of the software. These factors or indicators are found in
literature and / or by people of the software department and development department.
An important aspect about the software for the AD7 is that all software is written from
scratch. There was no useful software available, so the engineers had to write
everything themselves. So however this patient table is a derivative product, the
software of the previous AD5 table is not used to develop the software of the AD7.
The software of the AD7 exist out of a general part which makes sure all commands
are followed up in the right way with the system, or for example it makes sure that no
collisions occur with the rest of the Allura Xper system. For each movement of the
table, separate software is written. Each movement has its own packages. In this way
the software changes per configuration of the AD7.

Out of literature it is known that the more complexity in software, the more errors will
be produced (McQuaid, 1996). The complexity of the software code is the basic
information to take along, in order include the impact of software code on the
reliability.

As was found in literature, the amount of lines of code can influence reliability. More
lines of codes and longer syntax can result in slower performance of the program.
Also the amount and the intensity of loops in the software can influence the reliability
of a software program.
In this software code group errors found per volume of code must be considered as a factor influencing reliability. However, when errors are found by self or automotive testing, they are all solved. When all found problems are solved the program may be released. For the software engineers it was hard to give a factor that influences reliability, but they agreed on some of the metrics found in literature.

Another software aspect is that there are updates when the system is already in the field. As mentioned earlier, the focus of the project switched to meeting the deadline. Because of this, not all tests were conducted. New fully tested versions, together with improvements (for example indicated by field experience) will lead to new software updates. However of all updates for software only one small software change was made for the AD7. This software change did not give a big difference in the metrics of complexity related to the initial version. This data can unfortunately not be made available due to bad infrastructure. This problem will be elaborated later in this paper.

Each of these aspects mentioned in the current section can influence reliability. This is found in literature and indicated by the software development engineers. It is expected that less cyclomatic complexity and less lines of code, will result in fewer mistakes. Also is expected that a software update will lead to fewer mistakes in comparison with the previous version.

Interoperatability

Interface with peripheral equipment like printers or other devices which are not delivered by Philips Healthcare, but are necessary for the customer is called interoperatability. It is known that this situation can cause problems for the system while communicating with other devices. The main cause of this problem is software of the system which is not able to communicate with peripheral equipment. When the communication is not done in an orderly fashion, problems can occur. This may influence the reliability of the system.

This factor is almost impossible to use for reliability prediction, because it is not known what peripheral equipments is installed at what customer and what the properties of these equipments are. The factor came up front by the software and reliability engineers. A special team which focuses on interoperatability of systems was established during the development of the AD7.

Number of Reviews

The amount of comments or the percentage of comments which are not corrected during the design phase can influence reliability. A review of a part of the design can be made when the initial idea did not turn out to be as good as it was planned. Comments of engineers during development can arise out of testing or studying the design. Reasons for a lot of comments can be an insufficient quality of the design or a lot of intensive testing. A lot of intensive testing is favorable for a capital good. Costs will be lower when problems are found earlier in the design phase and can be adapted in the further design.

However, it is possible that the reliability decreases when the design is changed over and over again during the development. Some parts of the design are changed due to the many reviews while the rest is still according to the initial design.
This factor counts for every AD7 and is a constant factor. Therefore it can not be used for an input. Furthermore it is important to take into account that every problem found during the PDP is solved by the “Integration and testing” department before the design is released. After the change, the system is tested again.

Selection of Suppliers of components
The AD7 consists out of more than 3000 different components. Most of these components are not critical in sense that their reliability is low. But to prevent problems with components made elsewhere, the selection procedure of all components had to be done carefully. Selecting a supplier only on costs does not guarantee the quality which is needed, and thus reliability can be influenced.

Every type of component is coming from the same supplier, so there is no distinction in supplier for a certain type. This makes this factor constant for the AD7 and so not useful for the reliability prediction in the current case study.

Part per million level of Suppliers
Not all components are manufactured internally at Philips. At the beginning of the project it was decided by management that some crucial parts like the basic support table (which is the basic structure of the AD7) would be outsourced. This outsourcing is done cautiously, because the quality of the whole system depends on it. When a supplier was selected, together with Philips the components were tested to make sure the quality of the components were according to the required specifications. An indication of the quality of a supplier is faults found per Part per Million (PPM level). This level was investigated by Philips Healthcare to get an idea of how good a supplier was. PPM levels indicate that the quality of a product or even of a supplier. Coming up with a wrong judgment can eventually lead to reliability issues. This factor is indicated by the development department, but is hard to use because the information which is needed has to be gathered at suppliers from Philips Healthcare.

Number of movements
The AD7 can take 21 different configurations because of the combination of options which a customer can order. This means that each configuration is unique in its composition of movements. More movements will bring more complexity to the system, which can lead to more errors or failures (Bralla, 1995). This is why it is believed that this factor is crucial in the reliability prediction. The movements, which are discussed in section 3.2.2 under product description, have different levels of complexities. For example the height needs the same motor then the tilt movement; however the latter movement is far more complex in design. This is a reason to believe that this movement will bring more problems that the “simple” height movement.

Number of components
Not every component of the 3000 components in the AD7 is as sensitive as another. A lot of parts have proven themselves before in other projects or other industries. For example screws and bolts, steel frames, etc. More components means more parts where something can go wrong. So it can be that also the amount of components influence reliability of the system.
During design phase the development department decided to do a FMEA analysis to the most sensitive components of the AD7. This analysis resulted in thirteen critical components. The selection of these components was done very carefully and special attention was given to the implementation of these components into the system.

As mentioned in the description of the previous factor, different combination of movements will have different levels of complexity. When more movements are applied to a table, the table requires more components to let the movements work. However the percentage of extra components is not that big for an additional movement, the extra components are most of the time crucial components (Bralla, 1995). This means components with a lower mean time between failure (MTBF) values. This MTBF for the components plays also an important role on the influence on reliability, so we can see in the next section.

**Reliability of the components**

Each component has its own MTBF value. As we know from literature, when more components are combined, the overall MTBF will decrease (Lewis, 1996). Because during this project is looked to the complete AD7 system, and not only to it’s lose components, the MTBF of the table, will be lower then the lowest MTBF value of all components in the system. Regarding this, it is imaginable that the number of components can influence the reliability of the AD7 (Bralla, 1995).

This is an important factor that can have influence on reliability. However it should be considered that the components which are chosen have requirements on this MTBF value. Tests of the chosen components showed that the MTBF was above the required target stated by the hardware department (development).

**Quality of test design**

As mentioned before, hardware components will be tested, if necessarily together with the supplier, separately. The software department also tests their own developed codes. Software

When the software and hardware components were finished, they will be integrated by the “Integration and testing” department. This department uses test designs and test cases to make sure all fields of the product are covered. Problems found will be redirected to the department where the problem (likely) is caused.

When a lot of problems are found by the test cases, does not mean that the test cases are of high quality or that the product is bad. So the best way to find all problems of the product is to have a high quality test design. The quality can be expressed in coverage, amount of repetitions and so on. In the end the goal is to deliver a product where no problems will be found in the field, this is why it is important to design the tests is a way that it covers the usage of the system as it is in the field.

**Interface of the Table with the system**

The AD7 patient table is a subsystem of the overall Allura Xper system family. It is important that the table can communicate in a good way with the rest of the system, for example to prevent collisions with the C-arm or Stand. This requires a good interface. When the interaction of the table with the rest of the system is not correctly
organized, problems may occur which influence the reliability of the table, but also from the system. This factor came upfront during the brainstorm session, but is hard to take along since interaction with the overall system is the same for every AD7 configuration.

**Complexity of patient table**

A system like the AD7 is very complicated. There big amount of components and the enormous lines of code in all its variety makes the system very complex. It is not certain that highly complex systems produce more problems then simple systems. However, during the development of complex systems, a lot of issues should be taken into account. This makes the design more complicated. But when designing a highly complex system more attention is given to testing. Therefore, it is not necessarily the case that a complex system will produce more errors than a relatively more simple system. This is an important factor to consider when predicting reliability and so it is tried to take this along with the reliability prediction.

**Environmental Index**

When the system is in the field, an external factor can influence reliability. The environment where the system is installed can have influence on its performance. Humidity and temperature can affect components. In most of the specs of the components the range of values for environmental variables can be found.

Regarding the environment where the system is operated, other aspects are very important to take into consideration. The AD7 is a patient table, and sometimes used as an operating table. It can be that contrast fluid is spilled on the table and can stream into the system. Operational attributes like chirurgical equipment have to be installed on the table, but the biggest problem is probably the cables of all the peripheral equipment. As has been shown on pictures of the AD7, the system is nicely completed. However because of all peripheral equipment a lot of cables will hang around the table. This can deliver serious problems when the table moves. The next two figures give an impression of how a table looks like in real-time settings in comparison with the AD7 design.
It is believed that this factor is an important issue regarding reliability based on problems found in the field. Also from its predecessor (the AD5) this problem was known, and therefore the AD7 had already some positive changes. But the design by Philips Healthcare can not make a design for the cables of peripheral equipment of the customer himself. This is also the reason why this factor is hard to quantify: it is unknown what the customer does with his product. This factor is important to take along, however not all environmental aspects can be leveled and not all data can be collected.

**Calibration Error**

When a system is assembled for the first time in the OXB factory, some components have to be calibrated, especially the movable parts of the system. It can occur that this calibration is done on the edge of its acceptance area, or that the components deviate during transport. This calibration is important for the table to function, although the table will stop functioning with every occurring problem. This is why it is believed by some people of the development department that this calibration error can influence reliability. As described this factor is hard to quantify, since this problem is caused during transport or in the OXB.

**Maintenance Policy**

The maintenance of a system depends on the kind of service contract the customers agrees on with Philips Healthcare. In this contract it can be decided how frequent a service engineer comes by for preventive maintenance, or how often an update is provided. Because Philips Healthcare is still working on some parts of the AD7, these preventive maintenance or firmware updates can influence the reliability of the AD7. Reliability problems can be expected due to the long lifecycle. Some parts of a system are susceptible to degradation and / or random failures and these failures are often accepted (Brombacher et al., 2005).

It is also possible to indicate in the contract how fast an engineer must react on a problem, or a minimal downtime is guaranteed. This can also influence reliability because of fast reaction of the service engineer.

**Quality of documentation**

Reliability of the systems also depends on how people work with the system. A user should get proper documentation or even training to use the system in the correct way. A Service engineer should have good documentation about the system, and how to reach components to solve problems in a normal time. This is also important for maintenance. The quality of the provided documentation should be high to prevent wrong usage or incorrect handling by users or employees. Incorrect usage can cause failures in the system, and so affect reliability. The service innovation department makes documents for service engineers, and the costumers support department makes sure that the user uses the system in a correct way. These two departments work together to make these documents.

**Skills of the users**

The skill of the user can have influence on reliability, because the user must know what he is doing. When the user does not know what he is doing, it can be that he performs unwanted actions with the system. It could be that wrong combinations of
actions result in a failure of the system. This factor is partly related to the quality of the document factor.

This factor is hard to use, because it is not possible to know which people will work with a table and what their actions will be. Nevertheless it is tried in the design to take this into account.

**Training of the Users**

To prevent the previous factor, a user can be trained to get familiar with the system. He can be learned how to react and what to do in certain situations. This training must be given in an orderly manner. Most important is that the information comes clear to the user, and that there can not be any mistakes about using the system. A bad training is even worse than no training at all. Philips Healthcare is working on this, and sends engineers to the field to train users to work in a correct way with the system.

As long as no records are kept by Philips Healthcare that give an indication of the quality of their users, this factor is impossible to use for reliability prediction.

**Hardware version table**

At the beginning of the PDP of the table, Philips Healthcare decided that the basic patient table was outsourced. Another company, carefully selected by the Philips Healthcare, got the assignment to produce the basic structure of the patient table. Philips sees this as one component. The chosen manufacturer is located not that far from the plant in Best, since this is better for the cooperation and delivery time.

Although this basic structure of the table is the same for every configuration of the system, several new versions are released which should increase its performance.

**Usage profile**

The AD7 patient table is as we know a subsystem of the Xper Allura system. This system family can be used for several utilization (refer to section 3.2.1). For some applications the table is used more intensive then for others. More movements give more loads on the AD7. It can be that this intensity of usage has an influence on reliability. The idea behind this factor is that it is believed when a Xper Allura system is used for example for vascular purposes, the table will be used more intensive then for example for a cardio purpose. However an Xper Allura system in the field may have a biplane configuration for example, it is not necessary that the table will be used intensive. User profile can be better leveled when more data is available. For example the amount of certain commands that are used in the field. However to get this information, a logging system is needed which gives this information to Philips Healthcare.

**Purpose of use**

Most systems in the field are only used for examination in hospitals. However some systems are installed at universities or research facilities. It can be that the usage on these sites is differently than in hospitals. The availability of this factor is good, since in the database is indicated where the system is installed.
Development engineer Skills

The quality of the design of the product depends on the skills and experience of the development department and its engineers. Engineers with good skills and experience, from, for example previous products in the same line (e.g. AD5), will deliver a better design for the new product then inexperienced engineers, or engineers with other skills which are not applicable to the current product. This factor was found in literature and by interviewing people from the development department. Training of the service engineer will lead to better knowledge and so to better support. Philips Healthcare works on quality of its service and installation engineers. However, skills of a user develop over time, so hard to implement the right level for an engineer. Thereby it is almost impossible to track which engineer with a certain skill level worked or installed on a system on any given time.

Region / location

Not only can the user be a reliability factor in the field. Also the location or region where the system is installed can be of importance for its reliability. It could be that there is a difference in usage of a system which is placed a western country or in a third world country. Culture can play an important role in this. Also an aspect is the culture of the patient which is examined on the patient table. For example, on average, people in the United States are longer and heavier then people living in the Far East. However this is an average and only by using assumptions this factors can be used.

Faults found in the OXB

When a system is sold to a customer, it will be assembled in the OXB factory (One X-ray Best) before it is delivered to the customer. It is assembled in the exact same composition as it is sold in order to check whether all functions are working correctly. In this final test before the system is going to the customer, problems can be found. It could be that there is a correlation between the amount of problems found in the factory and the amount of problems found in the field. By talking to people of this assembly and testing department it became clear that this can influence reliability.

4.1.4. Selection Input Factors

In the previous section some reasons are mentioned why a certain factor can or can not be used as an input factor to predict reliability. For some factors it was already known by the identification of the factor, other factors were indicated not to be useful for the prediction when data was searched to quantify the factor. It can be that a factor is not chosen for more then one reason. These reasons are described in this section. When all problems are discussed it is possible to give a list of factors which can be used for reliability prediction.

One product: AD7

The most important reason for this project why a factor is not chosen is that each of the datasets used for reliability prediction, contains data of a unique system with its own configuration and location. A lot of factors which come up front by experts can not be used because of the case study only covers the AD7.

It is hard to compare a system mutual, but thanks to the variation in which the AD7 patient table can be delivered it still can be done. So factors which will be used to predict reliability are factors that can vary between each delivery of an AD7. This
final product of the PDP is a patient table with 21 different possible combinations of movements. Since only the AD7 was used for reliability prediction, the factors that can be used had to be variable among those 21 different configurations. So factors that do not change for the 21 configurations can not be used, because they are constant for each of these configurations. The factors with this property are listed below:

- Project Focus
- Hardware / Software Interface Integration
- PC and Operating system
- Interoperatibility
- Motion card
- Number of Reviews
- PPM level of Suppliers
- Reliability of the components
- Quality of test design
- Interface of the Table with the system
- Selection of Suppliers of components
- Quality of documentation

Other reasons that restrain a factor to participate in a reliability prediction method are data unavailability and data which is unable to level. These problems are discussed below.

**Data unavailability**

An important reason why factors can not be used for modeling is that there is not enough or no data at all to quantify the factors. In other words there is a data availability problem. Factors that can not be used by the prediction method because of this reason are:

- Hardware / Software Interface Integration
- External PC and Operating system
- Motion card
- Interoperatibility
- Number of Reviews
- Quality of test design
- Interface of the Table with the system
- Environmental Index
- Calibration Error
- Maintenance Policy
- Skills of the users
- Training of the Users
- Development engineer Skills

The latter three factors can not be taken into consideration for reliability prediction in the current research. However, Philips Healthcare is working on these subjects, and data will become available.

When data of some of the factors listed above can be made available, it still is not granted that the factor can be used to predict reliability. The reason discussed below explains why.
Unable to Quantify

To predict reliability we need several input parameters. Each parameter, which in this case is a factor that is believed to influences reliability, exists out of data of several levels. When it is impossible or very hard to make levels for a factor, then the factor can not be used for reliability prediction. For example it is very hard to give an indication about the skill level of an engineer. The factors that can not be used for reliability prediction because of the current reason are listed below.

- Hardware / Software Interface Integration
- External PC and Operating system
- Motion card
- Interoperability
- Number of Reviews
- Interface of the Table with the system
- Skills of the users
- Training of the Users
- Development engineer Skills

However these factors found will not be used for reliability prediction in this master thesis project, they can be of interest for Philips Healthcare when conducting reliability prediction using several derivative projects. For example when in the future a new patient table project will be started, these factors can be used as starting points.

To give an overview of the results of the chosen factors, a table is shown below.

Table 4-1 Overview used and not used factors

<table>
<thead>
<tr>
<th>Factors</th>
<th>Not used because</th>
<th>Factors used</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One Product</td>
<td>Data unavailability</td>
</tr>
<tr>
<td>Project management Focus</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Hardware / Software Interface Integration</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>External PC and Operating system</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Motion card</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Software code</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interoperability</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Number of Reviews</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Selection of Suppliers of components</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>PPM level of Suppliers</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Number of movements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability of the components</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Quality of test design</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Interface of the Table with the system</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Complexity of patient table</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Environmental Index</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration Error</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Maintenance Policy</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Quality of documentation</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Customer specification met in design</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Skills of the users</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Training of the Users</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
After discussing all the problems according the factors, the list with factors that are 
believed to have influence on the reliability and that can be used is discussed below.

**Selected input parameters**

Factors that are believed to influence reliability of the AD7 patient table will be used 
as input parameters for a reliability prediction method. These are only a few of all the 
initial factors.

1. **System Complexity**

Because the AD7 is a complex product, it was tried to give an indication of the system 
complexity of the patient table. A complexity index says something about the design 
of the product itself. The table had as we know 21 different configurations, which 
were built up out of the seven different movements. When it is known which 
configuration was selected, immediately can be said how many movements, 
components or Software complexity that systems has because these properties are 
linked one sided to the configuration. In other words every configuration had its own 
amount of movements, components and software packages. These three properties 
were indicated as possible influence factors for reliability. It was difficult to indicate a 
level for the system complexity for each configuration. There is no golden rule to 
define the complexity for the AD7. It was decided that the complexity of the AD7 
patient table was composed out of these three factors.

- Number of movements (1 until 7)
- Number of critical components (22 until 55)
- McCabe’s Cyclomatic Complexity Index (2,4 until 23)

These three factors were normalized and added together. Now the factor system 
complexity arises, which had a range of 0,4 until 3, where the highest number was the 
most complex configuration. Therefore the data of this parameter is scaled. A part of 
this data is shown in Appendix B

2. **Hardware version table**

The AD7 patient table is built up out of numerous components. The most important 
and biggest section of the table is the basic patient support. This section is the frame 
of the table in a whole, with a lot of hardware components already on it. It is delivered 
completely from only one supplier of Philips Healthcare. It could be said that this big 
part of the table is outsourced. During development and operation in the field, it was 
decided to adapt the design of which was delivered by this third party. Some hardware 
components were not of good quality, or it was decided that some extra components 
should be added. The current factor is used as an input parameter because it indicates 
which version this basic patient table support has. This parameter can have three 
different levels, namely the first version of the table which was a used in the first 
design what went to the field. And there were two update versions of the table during
3. Usage profile
As was indicated before, the Allura Xper system can be used for several purposes. Also was discussed that for vascular examination, normally spoken more movements were needed than the cardio examination. Using the table in surgery, even more movements probably will be appealed on. There is made a distinction between the following Allura Xper Systems.

<table>
<thead>
<tr>
<th>Cardio/Vascular X-Ray</th>
<th>FD10</th>
<th>FD20</th>
<th>FD10/10</th>
<th>FD10/20</th>
<th>FD20/20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiology</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vascular</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pediatric Cardiology</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrophysiology</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiology</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Neuro-radiology</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Surgery</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

As we can see has every Xper Allura system its own field of examination. The factor will be indicated by a nominal value for the 5 different Allura Xper FD designs. It is important to keep in mind that an AD7 in a FD20 system can be used more intensively as being part of a FD10 system; however this is not absolutely the case. As we can see an FD20 can be used for the same applications a FD10 is used for.

4. Purpose of Use
Most of the systems will be sold to hospitals or clinics. However, sometimes a university will buy a system for educational purposes (most of the time in cooperation with a hospital). It is also possible for a system to be installed in one of the Philips Innovation Centers for further investigation to the system. It is believed that the purpose of selling a system (clinical, technical innovation or educational purposes) can have an affect on the reliability of the system. This is why also this factor is used as an input parameter to predict reliability.

5. Region
The systems sold by Philips Healthcare can be installed all over the world. Different regions mean different habits and cultures. However there may be all these human differences, the clinical skill or knowledge are not region dependent. It can be that this factor can have an impact on reliability, which can be indicated by a reliability prediction method. It is interesting to investigate whether cultural background and country location can have an influence on reliability. As already mentioned in the previous section, there are statistical differences between the USA and the Far East. And for example some cultures will solve problems rather themselves, while others will call immediately when something is wrong and demand a service engineer to visit. All these aspects influence can the reliability and its indicators. Because data of this parameter will only give identifications to the regions, the data type is nominal.

6. Faults found in the OXB factory
The last factor, but certainly not the least important is Faults found by test engineers in the factory of Philips Healthcare. As mentioned before, a system is put together in the configuration it is ordered by the customer before it leaves the plant. The nice part of this factor is that it is possible to trace which system in the field established certain or a number of faults in the factory. It is believed that when a lot of faults are discovered in the factory, it can be expected that more problems will come up in the field. Whether this is the case could be investigated by the use of regression analysis.

In the factory only standard tests will be done, so not all problems will be brought to the light. But still it can be important to indicate found factors as early as possible, even just before the system will be delivered to customer. Because the data of this parameter can be zero or have an integer number, the data is scaled.

4.2. Defining reliability indicators

To predict reliability a reaction on the input factors must also be used. In this case reactions can be for example failures of (components of) the system in the field. Failures can be expressed in different ways. Customers can call with problems or failures to the call center, or failures can be logged via an internet connection. Also service engineers can report failures.

Reliability of the AD7 can be defined in several ways. Considering reliability of a system literature gives very often mean time between failures (MTBF) values or failure rates (amount of failures per period of time). The AD7 is not yet a year in the field and there is no MTBF from the field available. During the test phase a duration test was performed and the AD7 design was tested for its MTBF. Unfortunately this MTBF data can not be used because every the design is the same for every AD7 in the field and the MTBF test passed in the settings of the test.

From the field there are three indicators that say something about the reliability of the system. These three indicators are the only feedback available from the field.

- Calls from customers to the Call center;
- Field problem reports (FPR);
- Logging of software event codes.

These three outputs will be described below. Also is indicated why (or why not) the indicator can be used as an output factor for the reliability prediction method which will be chosen later on. This is in contrast with chapter 0 where at first; the factors that can influence reliability are identified. It is important to keep in mind that these are indicators of reliability not the exact reflection of the reliability of the AD7.

4.2.1. Calls from customers to the Call center

When a problem occurs at a site, and when the customer finds trouble with this problem, he is able to call the Call Center of Philips Healthcare. The call center is a service desk for customers. There is a procedure for call handling to solve a problem which comes from a customer. The steps are described below.

- First the helpdesk employee tries to solve the problem by giving the customer instructions. These instructions are set up logically and will solve most of the simple problems. These kind of simple problems are most of the time already
known by Philips, so good guidelines are available for the helpdesk employee and the concerned customer.

- When a problem can not be solved by the customer and the service desk employee, it is tried to reach the concerned system by the remote service network (RSN). In order to do this, the system should be connected to the RSN. By looking remotely into the system it is tried to see the cause of the problem. Software problems are tried to be solved by changing settings or by giving updates to the system.

- If it turns out that the problem still occurs, a service engineer will visit the site. The maximal time span the engineer is allowed before he visits the customer depends on the service contract and agreements with Philips. When the service engineer knows approximately the source of the problem, he can swap hardware components. Normally spoken the problem is solved now. The believed broken component can be investigated by Philips later on, when this is believed to be worth it. However it can be cheaper to just replace a believed broken part, and then investigate it on faults. Replacing a component will be noted on a job sheet. A job sheet is normally only produced when a component is replaced after a call has been made. Because a job sheet is normally spoken a result of a call, calls will be taken into consideration to indicate the performance / reliability of the AD7 and not the jobs.

All calls are stored in a database called Clarify. However for some unknown reason, some calls finish up in a database called HSC (unknown abbreviation). HSC is the predecessor of Clarify; it was previously used to store all calls. The most important difference for the master thesis project is that calls stored in the HSC database can not be linked to systems in the field (traceability problem).

Another important aspect of this factor is that for example data from USA is more easier handled and gathered then the same data from Japan because of language difficulties. As mentioned earlier, some customers will call earlier with a problem than others who will first try to solve the problem. Before call data is used for analyses it is filtered on reliability issues.

### 4.2.2. Field problem reports

The definition for a field problem report (FPR) at Philips Healthcare is not easy. The best way to describe it is that a field problem report is made by a service engineer as a result of major problems in the field or about often occurring problems. Several calls about the same complaint can be a reason to make a FPR, but this is not always the case. A service engineer can also make a FPR because of his own findings for example during installation or preventive maintenance.
Early wear out of components of a product or starting up problems can be causes to create a field problem report. Incoming FPRs are filtered inside Philips Healthcare by people who forward the problems to the concerned department. This department makes sure that the problem is fixed and the design will be adapted to prevent the problem from happening again. It can even be decided that the solution to the problem is applied to all the systems in the field. When this happens, a Field Change Order (FCO) is released. It is not by definition that every customer gets this FCO update, this can for example depend on the service contract that the customer has.

As mentioned these reports arise commonly when a specific problem keeps occurring among multiple systems or when the engineer gets the opinion (based on his experience) that the design is missing something. Because of this approach of making a FPR, it is impossible to link FPRs to specific systems in the field.

4.2.3. Logging of software event codes

The last possibility to get an idea of the performance of the system installed in the field is via log files of event codes generated by software. An event code is a number which indicates a type of event that can happen in the software of the product. Events can be divided into several groups (e.g. failure, error, warning and command). The software of the AD7 is written in such a way that when an event is detected, that it will log the concerned event code (so the number indicating the event). So for example when an error occurs in the software, the number of the specific error is logged. When the log file is considered the event code is found. Through this number and a list of descriptions, it can be found what the error is about. A sample of the list with event codes only applying AD7 is shown in the Appendix B.

Even codes of events that occur during operation in the field are logged to the system. When a system is connected to the Remote Service Network, the event codes can be downloaded to a database called RADAR. Event codes can be looked at until 6 months in the past. All the event codes are stored in the Data Warehouse (DWH) for an undefined time. By using the program ProClarity (Microsoft) the data in the DWH can be analyzed. However, only approximately 30% of data of the DWH can be used in ProClarity for analyses, because it was decided in Philips that the remaining 70% are not interesting for analyses. This 70% exist mainly out of informational event codes which are not interesting for reliability or performance analysis, and this will only slow ProClarity down.

Figure 4-5 Event code logging overview
As we can see, a lot data can be logged per system. And more important, thanks to the event codes; the importance of a logged event can be indicated. When selecting a certain system for a specific time period in ProClarity, a whole overview is created which gives the desired data. This information can be exported to Excel for further use or analyses.

Hence only call rate and Event codes rate are used for analysis.

Now that the reliability indicators are known which will be used for the analysis, in the next section a summary will be given of factors which will be used and the problems which were encountered during this search.

### 4.3. Evaluation & summary

All the input and output parameters which will be used in the model to predict reliability are described in the previous sections. To predict reliability datasets are needed. Each dataset should have a value for each input and for the output. The properties of the data used are shown below.

#### Table 4-3 Factors and Reliability indicators selected

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System Complexity</td>
<td>Scale</td>
<td>levels between 0.4 and 3.0</td>
</tr>
</tbody>
</table>
| 2. Hardware version table | Ordinal  | 1 Original version  
                          |                                                  | 2 First adapted version  
                          |                                                  | 3 Second adapted version                     |
| 3. Usage profile | Nominal  | 1 FD10 2 FD20 3 FD10/10 4 FD10/20 5 FD20/20     |
| 4. Purpose of Use | Nominal  | 1 Hospital  
                        |                                                  | 2 University & Hospital  
                        |                                                  | 3 Innovation Center                             |
| 5. Region       | Nominal  | 1 Europe & Mediterranean  
                        |                                                  | 2 North & Sought America  
                        |                                                  | 3 Asia & Far east                                 |
| 6. Faults found in the OXB | Scale  | Total faults found per system                  |

#### Reliability indicators

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call rate</td>
<td>Scale</td>
<td>Average calls per month</td>
</tr>
<tr>
<td>Event code rate</td>
<td>Scale</td>
<td>Average event codes per month</td>
</tr>
</tbody>
</table>

Most of the data of all parameters was found in the SAP database, which is a big ERP (Enterprise Resource Program) system in Philips Healthcare. Data about software was collected at the software department by using the quality overview program TICS Viewer. As already mentioned, data about faults in the factory are found in the FOREST database, call rate data was found in Clarify thanks to an analysis engineer and the Event Code rate was found by using RADAR and ProClarity.

#### 4.3.1. Problems encountered

The collection of this data gave some problems. The most significant problems which were encountered are described in the current section.
Data traceability

One of the biggest problems encountered during the master thesis at Philips Healthcare was the traceability of systems and its data. This problem was not foreseen at the start in contrast to the previous (making appointments) problem.

The problem was that inside Philips Healthcare almost every department uses its own traceability number for a system and uses its own database to store data. The data is stored obviously, in a way that the department needs it. However looking to data from an analyses point of view, the data is often stored illogical or interesting data is missing. The purpose to store data is not to analyze, but for use by the department.

When each department uses its own identification number to identify a system or none identification number at all, it is impossible to use the information stored without a traceability (comparing) table.

Most of the input parameters came from the Industrial kernel SAP database. In this database, a lot of numbers are unique for a system. When looking to the outputs, calls and event codes, it was assumed that probably one of all the unique codes available in SAP was good enough to link the systems to the output parameters. Eventually a way was found to overcome this problem partly. In the Figure 4-6 is shown that indicates where the data of all the factors came from.

Figure 4-6 Data traceability overview
The SAP Industrial Kernel database delivered most information. The data of the five factors were linked to each other by using System Code number (Allura Xper Family number) and unique Serial number.

Not all data was filled in correctly for the FOREST database. Consequences were that not all problems of AD7 tables are considered. And for example that problems caused by certain parts (movement parts like longitudinal or tilt) are not being considered, because no match can be found due to unclear or neglecting filling in fields.

The list which was used to indicate the RADAR systems turned out to be filled in manually a couple of years ago. This list was highly unreliable, and did not give more than a few linked datasets. By manually searching and by help of other engineers of Philips Eindhoven, most of the systems could be linked to their output via a detour.

The data from the call center also had some issues. Not all numbers filled in could be linked to the Equipment number of SAP MP1. The numbers that could be linked were finally via another table linked to the list of factors.

Data availability
The first AD7 patient table was released to the field in September 2007. So at the end of June 2008, there were 306 systems in the field which had an AD7 patient table. This is a good number for analysis, if all data would be available. The problem lay at the output parameters. An engineer who reached all AD7 calls filtered on reliability could bring data until March (USA) and April (Europe & Asia). This left 207 systems for call rate. Of those 207 systems only 18 calls were possible to trace. There was more data available in another database, but this data was not linked. This would be a major setback for the analysis. More data would be available when the engineer is coming back from holiday and starts analyzing the calls from March / April until present.

Of the event codes only little data was available because the systems in the field are not all connected to RADAR and the identification of each system was not accurate enough. Eventually only 18 systems were linked of the 306 in the field. In half a year more data will be available, because the inaccurate data list is being cleaned up and corrected.

4.3.2. Final data set
Now the available data of all 306 patient tables installed in the field is collected, a part of the list is given in Appendix E.

As is shown in this appendix, all factors and the configuration number of the table are inserted. The call rate is shown; only one call rate higher then zero is visible. Of the event codes rate no value is visible, because in the sample shown no system had an event code generated that could be traced.

Now all factors and data are known that are used to predict the reliability of the AD7 patient table it is also known what the properties the reliability prediction method must be able to handle. This decision and the modeling itself will be made in the next section.
5. Modeling & analyses using the Case Study

In this chapter the reliability prediction of the AD7 patient table will be discussed. First a suitable method is chosen based on the factors identified in the previous section. The theory behind this chosen method is discussed in Appendix F. The theory is applied to the case study in paragraph 5.2 and paragraph 5.2. Finally recommendations to improve findings are given in paragraph 5.4.

5.1. Choosing a prediction method

As we look back to the problem definition, we need a reliability prediction method that can handle factors that influence reliability. Classical methods like the military handbook are not capable of solving today’s reliability predictions. From literature there are several candidates. Three of them are listed below:

- Multiple Regression Analysis;
- Bayesian Believe Networks;
- Artificial Neural Networks.

Multiple regression analysis

Multiple regression analysis is the simplest prediction method of this list. It uses the data to create a function which fits the output data the best (Hair et al., 2005). Unfortunately this method is based on linear regression, and can not handle non linear related data which can be the case by using the factors identified of the AD7.

Bayesian Believe Network

Bayesian statistical methods are widely used in probabilistic risk assessment (PRA) because of their ability to provide useful estimates of model parameters when data are sparse (Siu and Kelly, 1998). The Bayesian believe network is a prediction method that is able to incorporate a wide variety of information types, including expert judgment. In abstract, Bayesian Networks use field data to update the current (prior) reliability distribution to get a more accurate reliability distribution (posterior). Bayesian Believe networks allow one to learn about causal relationships and can readily handle incomplete data sets. The Bayesian Believe network has become a popular representation for programming uncertain expert information in professional systems (Heckerman 1996). Bayesian networks needs to set prior distributions, which can be a disadvantage (especially when this is hard to indicate), depending on the analytical problem (Liu and Logvinenko, 2003).

Artificial Neural Network

The Artificial neural network method (commonly referred to as neural networks or NN) is a prediction method that works like a black box approach, and is based on the neurological operation procedure of the brain. A neural network is basically a machine that is designed to model the way in which the brain performs a particular task or function (Haykin, 1994). The basic element of a neural network is training the black box. The NN learns from the examples by constructing an input-output mapping for the problem at hand (Haykin, 1994). Another most important benefit of neural networks is that it can handle nonlinear data. Also a neural network can easily be retrained, so when new data is available, the same network can be used. This can be very useful when minor changes appear in the operating environment conditions.
The chosen prediction method

The Bayesian Believe network is one of the possible options to use as a reliability prediction method. The Bayesian Believe network is good in programming uncertain expert information in professional systems (Heckerman 1996). The uncertain expert information comes from the expert judgments. The elicitation of judgment from experts to both structure and to instantiate the Bayesian Believe network is often challenging (Sigurdsson, 2001). The data found in the case study mostly concerns statistical data and only minor indications of causal relationships were found during interviews and the brainstorm session. Bayesian Believe networks can also handle statistical data, but they can perform better with causal relationships indicated by for example expert judgments. Unfortunately time did not allow digging deeper into the causal relationships experts make about certain factors. Furthermore it is not necessarily so that using Bayesian Believe networks come up with a more accurate outcome using expert judgment then other prediction models. The quality of Bayesian Believe networks can easily be influenced by opinions of experts. For example, when an expert indicates a certain factor that influences reliability, but which in reality does not have any influence on reality whatsoever, the Bayesian Believe network will always use the factor to model because the expert said so. There is no validation indicator directly available for this method, which can be treacherous when the result in inaccurate.

On the other hand, regarding the case study, neural network seemed a good choice to predict reliability since this method can use the factors and its data that are identified in the case study as input parameters to predict reliability. This is possible because neural networks can handle the properties of the found factors like nonlinearity. Data found in the study case could change or update very often because of new found data sources available. This is no problem for the neural network method since adapting the model and retraining can be done very fast. This is also an advantage when new data becomes available in the near future at Philips Healthcare. If in the future also subjective data becomes available, this is no reason to switch necessarily to Bayesian Believe networks, since neural networks are also able to handle this type of data. When a factor is put into the NN which does not have any influence on reliability, statistics will tell, and the network will automatically ignore the certain factor, in contrast with the Bayesian Believe network. But the opposite is also possible; a neural network can make a relationship between two variables based on data while in a real situation the independent variable does not change the dependent variable.

The theory behind Neural Networks is elaborated in Appendix F to get a better idea about how this method works and its properties.

Also a multiple regression analysis is conducted to look for any relationships which could lead to a good reliability prediction. The regression analysis is discussed in paragraph 5.2.

5.2. Regression analysis

Models like regression analysis can indicate simple linear relations. These statistical analyses models can be used to estimate reliability. Hair et al. (2005) shows that multiple regression analysis can be performed, since the situation of this case study is:
One dependent variable (metric) = six independent variables (metric & non metric)

The sample size affects the possibility to generalize the result of a regression model. Hair et al. 2005 gives the general rule that the ratio of observations to independent variables should never be lower than 5:1. However this is the minimum ratio, it is better to have 15 or 20:1. Since there are 6 independent variables in the AD7 model, this ratio is easily satisfied.

5.2.1. Correlations

To see whether there is correlation between the inputs (independent variables) and the output (dependent variables) a correlation table is shown below which is determined by using the statistical program SPSS.

Table 5-1 Correlation Call rate

<table>
<thead>
<tr>
<th>Factors</th>
<th>Call Rate</th>
<th>Usage Profile</th>
<th>Faults in OXB</th>
<th>Hardware version</th>
<th>AD7 Complexity</th>
<th>Purpose of use</th>
<th>Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call Rate</td>
<td>1</td>
<td>-0.016</td>
<td>0.089</td>
<td>-0.102</td>
<td>-0.107</td>
<td>0.026</td>
<td>-0.22</td>
</tr>
<tr>
<td>Usage Profile</td>
<td>-0.016</td>
<td>1</td>
<td>0</td>
<td>0.285</td>
<td>0.486</td>
<td>0.044</td>
<td>-0.148</td>
</tr>
<tr>
<td>Faults in OXB</td>
<td>0.089</td>
<td>0</td>
<td>1</td>
<td>-0.013</td>
<td>0.097</td>
<td>0.112</td>
<td>-0.062</td>
</tr>
<tr>
<td>Hardware version</td>
<td>-0.102</td>
<td>0.285</td>
<td>-0.013</td>
<td>1</td>
<td>0.217</td>
<td>-0.033</td>
<td>-0.209</td>
</tr>
<tr>
<td>AD7 Complexity</td>
<td>-0.107</td>
<td>0.486</td>
<td>0.097</td>
<td>0.217</td>
<td>1</td>
<td>0.272</td>
<td>-0.165</td>
</tr>
<tr>
<td>Purpose of use</td>
<td>0.026</td>
<td>0.044</td>
<td>0.112</td>
<td>-0.033</td>
<td>0.272</td>
<td>1</td>
<td>0.089</td>
</tr>
<tr>
<td>Regions</td>
<td>-0.22</td>
<td>-0.148</td>
<td>-0.062</td>
<td>-0.209</td>
<td>-0.165</td>
<td>0.089</td>
<td>1</td>
</tr>
</tbody>
</table>

Sig. (1-tailed)  

<table>
<thead>
<tr>
<th>Factors</th>
<th>Call Rate</th>
<th>Usage Profile</th>
<th>Faults in OXB</th>
<th>Hardware version</th>
<th>AD7 Complexity</th>
<th>Purpose of use</th>
<th>Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call Rate</td>
<td>0.409</td>
<td>0.102</td>
<td>0.073</td>
<td>0.064</td>
<td>0.354</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Usage Profile</td>
<td>0.497</td>
<td>0</td>
<td>0</td>
<td>0.265</td>
<td>0.017</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Faults in OXB</td>
<td>0.102</td>
<td>0.497</td>
<td>0.426</td>
<td>0.084</td>
<td>0.055</td>
<td>0.188</td>
<td></td>
</tr>
<tr>
<td>Hardware version</td>
<td>0.073</td>
<td>0</td>
<td>0.426</td>
<td>0.001</td>
<td>0.317</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>AD7 Complexity</td>
<td>0.064</td>
<td>0</td>
<td>0.084</td>
<td>0.001</td>
<td>0</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>Purpose of use</td>
<td>0.354</td>
<td>0.265</td>
<td>0.055</td>
<td>0.317</td>
<td>0</td>
<td>0.102</td>
<td></td>
</tr>
<tr>
<td>Regions</td>
<td>0.001</td>
<td>0.017</td>
<td>0.188</td>
<td>0.001</td>
<td>0.009</td>
<td>0.102</td>
<td></td>
</tr>
</tbody>
</table>

There is no significant correlation between input parameters (independent variables) and the output parameter (dependent variable). There are no significant correlations found among the dependent variables. Only one promising correlation showed up of medium relevance (0.4 < r < 0.6). This correlation was among Usage Profile and System Complexity (r = 0.486). Usage Profile indicates whether the system where the AD7 is part of, is a mono or biplane. This is coherence with the usage (cardio, vascular, surgery, etc.). System Complexity is as we know determined from amount of components, movements and software complexity. It is imaginable that these two parameters have some kind of relationship when considering that an Allura Xper system with more sophisticated purposes needs a table with more options, hence higher complexity. Vice versa is this also applicable, simpler purpose usually has sufficient with a less complicated patient table.

No correlation found among the dependent and independent variables means that it is unlikely to come up with a promising regression model. This will be more elaborated by the use of the model summary (statistical properties of the model) and an ANOVA table.
5.2.2. Call rate

This section will describe the regression analysis which was performed by using the call rate data for the independent variable. In the table below the summary of the model is shown.

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
<th>R Square Change</th>
<th>F Change</th>
<th>df1</th>
<th>df2</th>
<th>Sig. F Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.318634</td>
<td>0.101527</td>
<td>0.074438</td>
<td>0.055686</td>
<td>0.101527</td>
<td>3.747837</td>
<td>6</td>
<td>199</td>
<td>0.001481</td>
</tr>
</tbody>
</table>

Some conclusions from the regression model by using call rate as the dependent variable are here discussed. The R type factor is 0.314 which mean there is not much correlation among the variables. The R square indicates that only 10.2% of the dependent variable can be explained by the regression model. This means that the regression model is not likely to give a good prediction for the call rate.

<table>
<thead>
<tr>
<th>Model</th>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig. F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regression</td>
<td>0.06973</td>
<td>6</td>
<td>0.011622</td>
<td>3.747837</td>
</tr>
<tr>
<td>Residual</td>
<td>0.617076</td>
<td>199</td>
<td>0.003101</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.686806</td>
<td>205</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The F ratio found in the ANOVA table above indicates that there is a systematical difference among the groups. The reasons for this disappointing result of the regression analysis can be because of the data which is used for the dependent variable. There were 206 datasets, but only 14 sets had a value bigger then zero, but still below one.

Finally the found coefficients for the estimation model are given in the table below. Unfortunately these are not usable to create an equation (Table 5-4 Coefficients)

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td>0.080724</td>
<td>0.020757</td>
</tr>
<tr>
<td>Usage Profile</td>
<td>0.003041</td>
<td>0.0035</td>
</tr>
<tr>
<td>Faults in OXB</td>
<td>0.002541</td>
<td>0.00219</td>
</tr>
<tr>
<td>Hardware version</td>
<td>-0.02164</td>
<td>0.011558</td>
</tr>
<tr>
<td>AD7 Complexity</td>
<td>-0.01929</td>
<td>0.008445</td>
</tr>
<tr>
<td>Purpose of use</td>
<td>0.009477</td>
<td>0.00796</td>
</tr>
<tr>
<td>Regions</td>
<td>-0.02</td>
<td>0.005154</td>
</tr>
</tbody>
</table>

The regression model was not able to come up with a good estimation model. Maybe this is because the data used is nonlinear related. In the next paragraph the neural network is applied to try to find a better estimation model as the regression model described above.
5.3. **Prediction with Neural Networks**

The Neural Network will be used to create a model to predict reliability of the AD7 patient table. It is tried to find a relationship between the factors that are believed to influence the reliability of the table and the reliability indicators of the patient table. However the data and then especially the output data seems not optimal because of the low variance in call rate, it is tried to get a Neural Network model that predicts the reliability of the AD7.

Since it turned out that not all factors can be used for the model, the neural network will be used to predict the reliability by using six input parameters and the reliability indicator call rate.

To perform this prediction modeling the several programs can be used. MATLAB 7.5.0 (R2007b) provides two toolboxes to solve problems with NN, one GUI version (Graphical User Interface) and one syntax-based version. The syntax-based version is too elaborated for this study. SPSS 16.0 provides a Neural Network module in a GUI form. The SPSS version is used to perform the prediction because this is more elaborated and more clear then the MATLAB GUI version.

**5.3.1. Data used**

Unfortunately not all factors that were identified (see chapter 4) can be used because of several reason also mention in that chapter. Therefore the Neural Network will be used to predict the reliability of the AD7 patient table on basis of call rate (which has a scale level of measurement) and by the six parameters:

- System complexity (scale);
- Usage (Nominal);
- Purpose of use (Nominal);
- Region (Nominal);
- Faults found in OXB (Scale);
- Hardware version (Ordinal).

Using the call rate of the available output parameters to train the NN gives a bigger dataset. This means that 206 datasets are used for training, testing and validation. We also know that only 14 datasets have an output which is greater then zero.

**5.3.2. Construction the Neural Network**

A lot of properties of the NN can be set by the user. Not only the amount of training, testing and validation data can be set, but also a contribution about the transfer function and the architecture of the model can be given. Since the data is implemented in SPSS, the scales of measurement (ordinal, nominal and scale) are automatically set when using the Neural Network. The module now generates automatically dummy variables for nominal data. When input parameters have the scale level of measurement, SPSS gives the opportunity to rescale them in order to improve network training.

**Number of neurons**

As mentioned a lot of settings can be adjusted in the program. Because of the exploratory property of this study in combination with the amount of data is available,
it is decided that the multilayer perceptron has one hidden layer. The amount of neurons in the hidden layers dependents on the number of datasets.

There are several ways to indicate the amount of neurons for the hidden layer. SPSS had even an option where the program itself determines this number of neurons. It is suggested in literature that the best way to find this, and also other settings in neural network, is trial and error. This is because every problem has its own characteristics, and there is no golden rule that determines this. A heuristic for the amount of neurons in the hidden layer is 10 datasets per weighted connection (Zhang et al. 1990). But it is stated that more datasets is better for the performance of the network. Because calls were only available until March / April, this delivered 206 datasets. Regarding the rule of thumbs of (Zhang et al. 1990) this gives 20 weighted connections. Since there are six input parameters, and one output parameter, the amount of neurons in the hidden layer will be three (6 input * 3 neurons + 3 connections to the output). Another general rule of thumb is to determine the number of hidden units as the half of the total input and output neurons (7 / 2).

So from dataset availability and from input parameter point of view three neurons in the hidden layer seems a good start. To get a better idea, and to follow the trial and error recommendation, the network is also modeled with more neurons.

Other settings in SPSS
In SPSS a lot of settings can be adjusted. SPSS is also able to create automatically a neural network. In the following section is described what the manual settings will be to train the NN.

As activation function, the sigmoid function is used in the hidden layer, when the dataset doesn't require a special function, this a good function to use (Haykin, 1994). Because the output is has a scaled type of measurement level, the identity function is chosen. When program SPSS would chose the settings automatically, it would have chosen the same functions. As mentioned, SPSS offers more opportunities to modify all kind of settings. Since the dependent variable has a scaled type of measurement level, rescaling can be applied. The standardized rescaling method is chosen. The training options allow fine-tuning the optimization algorithm. However these settings will generally not be changed, only when the program runs into problems with estimation.

The 206 datasets will be used to train, validate and test the network. It is recommended that the largest part of the datasets available will be used for training the network. Validation and testing may be divided equally. The datasets will be assigned randomly to a group. Normally these percentages are 60% - 20% - 20% or 70% - 15% - 15%. When indicating these percentages, SPSS will determine the exact distribution which is used for the modeling. These values can deviate a little form the given percentages.

5.3.3. Training the / performance of the neural network
Now all data and settings are known, the NN can be trained and the outcome will be discussed. The only settings which will be changed are percentages of training - testing - validation and the number of hidden neurons.
To get better feeling about the model quality, each model is trained four times with the same settings. On the right side, the average of each test model is given to get a quick idea of the results of a model. The standard deviation is shown to see how much the model varies under four times of testing. The results are shown in Table 5-5.

Table 5-5 NN results

<table>
<thead>
<tr>
<th>hidden neurons</th>
<th>partitioning</th>
<th>purpose</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sum of errors</td>
<td>Relative error</td>
<td>Sum of errors</td>
<td>Relative error</td>
<td>Sum of errors</td>
<td>Relative error</td>
<td>Sum of errors</td>
</tr>
<tr>
<td>2</td>
<td>60% Training</td>
<td>63.209</td>
<td>0.97999</td>
<td>46.55</td>
<td>0.71616</td>
<td>45.4034</td>
<td>0.77613</td>
<td>58.9305</td>
</tr>
<tr>
<td></td>
<td>20% Testing</td>
<td>2.8483</td>
<td>1.27972</td>
<td>65.606</td>
<td>0.86189</td>
<td>14.0723</td>
<td>0.73931</td>
<td>29.392</td>
</tr>
<tr>
<td></td>
<td>20% Validation</td>
<td>1.00151</td>
<td>1.37235</td>
<td>0.4311</td>
<td>1.43631</td>
<td>1.06032</td>
<td>0.45963</td>
<td>6.0568</td>
</tr>
<tr>
<td>3</td>
<td>60% Training</td>
<td>53.271</td>
<td>0.83236</td>
<td>62.112</td>
<td>0.98591</td>
<td>50.8957</td>
<td>0.95132</td>
<td>56.421</td>
</tr>
<tr>
<td></td>
<td>20% Testing</td>
<td>75.568</td>
<td>0.72568</td>
<td>24.644</td>
<td>0.98996</td>
<td>12.644</td>
<td>0.9718</td>
<td>10.542</td>
</tr>
<tr>
<td></td>
<td>20% Validation</td>
<td>0.6184</td>
<td>1.02094</td>
<td>1.02534</td>
<td>0.97384</td>
<td>0.90963</td>
<td>0.05384</td>
<td>6.4589</td>
</tr>
<tr>
<td>4</td>
<td>60% Training</td>
<td>53.067</td>
<td>0.69945</td>
<td>61.448</td>
<td>0.96768</td>
<td>59.8699</td>
<td>0.94279</td>
<td>47.049</td>
</tr>
<tr>
<td></td>
<td>20% Testing</td>
<td>20.466</td>
<td>0.82912</td>
<td>7.4344</td>
<td>0.94252</td>
<td>12.389</td>
<td>0.93411</td>
<td>0.9411</td>
</tr>
<tr>
<td></td>
<td>20% Validation</td>
<td>0.89496</td>
<td>0.98527</td>
<td>1.16545</td>
<td>1.06626</td>
<td>1.11649</td>
<td>0.15782</td>
<td>1.8914</td>
</tr>
<tr>
<td>5</td>
<td>60% Training</td>
<td>39.627</td>
<td>0.63914</td>
<td>38.133</td>
<td>0.86185</td>
<td>60.1882</td>
<td>0.97867</td>
<td>55.726</td>
</tr>
<tr>
<td></td>
<td>20% Testing</td>
<td>32.548</td>
<td>0.77461</td>
<td>6.2952</td>
<td>0.78262</td>
<td>31.6568</td>
<td>1.01923</td>
<td>4.7096</td>
</tr>
<tr>
<td></td>
<td>20% Validation</td>
<td>0.91888</td>
<td>1.10051</td>
<td>1.03243</td>
<td>1.0399</td>
<td>1.02293</td>
<td>0.03907</td>
<td>2.7362</td>
</tr>
<tr>
<td>3</td>
<td>70% Training</td>
<td>72.167</td>
<td>0.898</td>
<td>51.237</td>
<td>0.78224</td>
<td>52.282</td>
<td>0.73632</td>
<td>54.179</td>
</tr>
<tr>
<td></td>
<td>15% Testing</td>
<td>a</td>
<td>17.403</td>
<td>0.89008</td>
<td>31.2909</td>
<td>0.93331</td>
<td>35.2148</td>
<td>0.90223</td>
</tr>
<tr>
<td></td>
<td>15% Validation</td>
<td>0.98044</td>
<td>3.30769</td>
<td>0.97177</td>
<td>0.75626</td>
<td>1.50403</td>
<td>1.15826</td>
<td>39</td>
</tr>
<tr>
<td>Auto settings</td>
<td>60% Training</td>
<td>40.253</td>
<td>0.63854</td>
<td>62.244</td>
<td>0.96552</td>
<td>50.7505</td>
<td>0.83886</td>
<td>62.432</td>
</tr>
<tr>
<td></td>
<td>20% Testing</td>
<td>1.6914</td>
<td>0.61059</td>
<td>1.2821</td>
<td>a</td>
<td>26.8981</td>
<td>0.86657</td>
<td>17.404</td>
</tr>
<tr>
<td></td>
<td>(4,5,4,5,4)</td>
<td>20% Validation</td>
<td>1.0116</td>
<td>0.94155</td>
<td>0.8125</td>
<td>1.03688</td>
<td>0.95063</td>
<td>0.09321</td>
</tr>
</tbody>
</table>

*Cannot be computed. The dependent variable may be constant in the testing sample.*

The table above displays information about the results of training and applying the final neural network to the validation sample. This table and its results will be discussed below.

- The Sum-of-squares error is the error function that the network tries to minimize during training;
- The relative error is the ratio of the sum-of-squares error for the dependent variable to the sum-of-squares error for the "null" model, in which the mean value of the dependent variable is used as the predicted value for each case.
- The relative errors are fairly constant across the training, testing, and validation samples, which give some confidence that the model is not over trained.

In all cases the estimation algorithm stopped because the error did not decrease after a step in the algorithm. The relative error for each scale-dependent variable is the ratio of the sum-of-squares error for the dependent variable to the sum-of-squares error for the "null" model, in which the mean value of the dependent variable is used as the predicted value for each case.

5.3.4. Findings

The result of the performed neural networks shows that the prediction method with this data can not be used for reliability prediction, because the error is too big. Even
when more settings are tried to create an accurate model, the squares error stays too big. Also all the relative errors are quite bad, since they are all close to 1. This means that the created model is not accurate enough to give a good estimate. The neural network can not predict a realistic performance of the AD7 patient table.

5.3.5. Event codes

Also some data was available about the event codes rate. This is to little data to perform a NN modeling. However correlation is found between some event codes. The result of the correlation is shown in Appendix G. When for example event code 63001001 occurs, then the even codes starting with 63001019 until 63001028 also occur. This can be useful for the maintenance engineers to investigate in order to apply preventive maintenance. The event codes can not be used for prediction, but it can give reasons to perform preventive maintenances.

5.4. Recommendations for better findings

Some recommendations which were found during data analyses are described in this section. Recommendations for getting better results is split up in two categories, data related and model related, which are described below.

5.4.1. Data related

Sample size

The sample size was sufficient for regression analysis. Though more data would be better for modeling with NN, since then more neurons can be used in the hidden layer which is better to optimize complicated prediction problems.

Input parameters

The amount of input parameters is sufficient in the sense that it is possible to use NN and to perform regression analyses. More input parameters means that more datasets are needed, which is a problem for NN, because when no extra samples are available, this will mean that the amount of neurons in the hidden layer should decrease. This is not a nice situation to deal with, since it is recommended (based on rules of thumb) to use only approximately three neurons (see paragraph 5.3.2).

Another recommendation for better findings regarding the input parameters is to implement other input parameters. Unfortunately not all initially found factors were possible to use as an input for the model used. As mentioned before, this had several reasons which. For most of these problems, it is not likely that a solution will be found in the near future.

Output parameters

Two output parameters were found available in the current research as reliability indicators for the AD7 patient table. Both parameters had problems regarding the availability of data.

The most data available was for the call rate. Thanks to this parameter, 206 data sets were available. However of these 206 AD7 patient tables which were in the field, only 18 calls were found in the data base of the call center. Some cases had 2 calls, which lead to the fact that only 14 datasets had an outcome greater then zero. Because calls
are transferred to call rate per month, the output parameters are all smaller than 0.5. Having only 14 outcomes (and the rest zero) is less than 7% of all available datasets. It is hard to train a network with this, since more than 93% of the data has the same output. Having only 14 calls can mean that the product is very good, and only few customers have reasons to call, however, it can also be because not all AD7 related calls were found or not correctly noted in the database. It is recommended to train the network with more variation in the output instead of having 93% of the data all the same value.

The data which was available of the event codes was all useful, but because of traceability problems only a small percentage of all 306 AD7 patient tables in the field could give event code data. This problem can be solved by linking all systems to the Remote Service Network of Philips Healthcare, and also to RADAR. But when this happens, the traceability of the systems itself should also be improved. So that it is possible to now what systems gives the event codes.

When these problems could be overcome, and more data will be available and when the used factors are important considering influencing reliability, it can be stated that it is likely that the performance of the Neural Network regarding reliability prediction will increase.

When more event codes are available because of improvements on the RADAR network, it would be interesting, and maybe also better for the reliability prediction, to use both call rate and event code rate as output for the network. This means that two dependent variables will be used with the same set of independent variables. Both SPPS regression analysis as the Neural Network method are able to model with two output parameters.

5.4.2. Model related

Regarding multiple regression analyses no extra recommendations can be given, since this is a straightforward analyze method.

When better data is available it is recommended that more different settings for the Neural Network with SPSS are tried. It can be that for example other activation function with more data / inputs can have influence on the performance of the NN in comparison with the current situation. Better correlated data and better representative output data will give more freedom to try more different types of activation and optimalizing functions and other settings to improve the performance of the NN. Finding the most optimal setting for a specific problem has to be done by trial and error. There is no golden rule for certain types of problems to approach the prediction.
6. Conclusion & Discussion

This master thesis project covers the research of predicting reliability of a complex system. The current chapter will summarize the conclusions of this research. First research questions are answered and in the paragraph 6.2 these answers will be discussed.

6.1. Research questions

Here short answers will be given to the research questions which are investigated by help of the case study at Philips Healthcare. The first research question was:

What are the factors that can influence reliability of the system?

The following factors were identified by the use of a case study at Philips Healthcare:

- Project management Focus
- HW / SW Interface Integration
- External PC and Operating system
- Motion card
- Software code
- Interoperability
- Number of Reviews
- Selection of Suppliers
- PPM level of Suppliers
- Number of movements
- Number of components
- Reliability of the components
- Quality of test design
- Interface of AD7 with the system
- Complexity of patient table
- Environmental Index
- Calibration Error
- Maintenance Policy
- Quality of documentation
- Skills of the users
- Training of the Users
- Hardware version table
- Usage profile
- Purpose of use
- Development engineer Skills
- Region / location
- Faults found in the OXB

The identification of this list of factors is done on base of literature and expert opinion from the people who were involved in the PDP of the system under study.

The second research question is:

How to predict reliability of the system using these influential factors?

This research question is harder to answer. To predict reliability in this case study the Neural Network method was chosen based on several arguments, among which the factors that Neural Network can handle factors that influence reliability during the PDP. Of all factors indicated by the first research question, only a few could be used for reliability prediction. This makes the model less accurate and drifts away from the reality, which is unfortunate for the outcome of the reliability prediction. Reasons and recommendations about this low number of levels used are discussed in the next paragraphs.

Although not all factors could be taken into account, it can be stated that the factors which are used are able to support the Neural Network. The data of these factors were in the right format for implementation.
Looking to the results of the prediction method, it is found that the errors are too big, and the method can come up with a good estimation model. This is probably due to reliability indicator "call rate" which is not diverse enough, due the fact that only 10% of the call rate was higher then zero.

Finally a multiple regression analysis was tried. Unfortunately the results of this turned out to be inaccurate too.

6.2. Discussion

The methodology which was followed to accumulate all the factors that can influence reliability yielded a variety of possible factors. Experts from every department who were involved with the PDP of the AD7 patient table took part in identifying the factors. Also numerous literature papers were consulted to support or identify factors that may influence the reliability of the patient table. This is why it is believed that all important factors are indicated. Unfortunately the scant availability of data prevented that a lot of factors could not be used to model a prediction of the AD7. This is why it is impossible to state with 100% certainty that the indicated factors are all the factors that have influence on reliability.

Also the dependent variable, the reliability indicator, was not of sufficient quality and quantity to create a good estimation model. On the other hand, when all data of all factors would be available, the Neural Network would be unable to create a qualitative estimation model, regarding the relative small amount of data sets available. This is due to the guidelines of neural network as was elaborated in paragraph Appendix F, which state that for every extra synapse, ten extra datasets must be available. Higher the amount of factors identified, higher the dataset needed for the network to have a better prediction.

Another point of discussion is not the quantity of the call rate data, but the quality. The Neural Networks method requires diversity and variance in the set of data, also regarding the output. Normally for reliability prediction, a MTBF value is chosen, however this is not available in the cases study, since the system is only a relative short time in the field, and because it is hard to give such a value based on calls or event codes in the field. Engineers at Philips Healthcare also don’t have any idea yet of the MTBF of the AD7. Because an indication of the reliability of the system in the field is call rate or event code rate, this is taken as an output for the prediction method. It should be reminded that this is only an indicator. Thereby comes that the data exists for more then 90% out of zero calls and for the remaining part out of values between zero and one. This does not give the variance needed by the Neural Network; hence the training can not be optimal. It is unknown whether the variance in output is structured. More noise than variance makes it impossible to create a good estimation model.

Regarding the problem analyses of chapter 1 where is stated why this master thesis was chosen, it is possible to state that reliability can be predicted by use of Neural Network for as far as investigated in this master thesis project. Neural Networks was able to take along all factors that were identified and of which data was available. However, a good estimation model could not be given since data did not allow the Neural Network to model properly. In chapter 7 recommendations are suggested to
lesser the problems faced in data collection and modeling, in order to have a better reliability prediction.

Nevertheless the identified factors that may influence reliability can be of interest for Philips Healthcare. Addressing the factors is an extra reminder or indication for the departments to think of. Also, these factors can be of interest for Philips Healthcare when conducting reliability prediction using several derivative projects. For example when in the future a new patient table project will be started, these factors can be used as starting points. And when the reliability prediction is done again by using Neural Networks and the current factors are still of use, a prediction model can be created with data of the AD7 used to train the network and can be tested with input data of the new Patient Table. The prediction results can be validated when the reliability of the new table can be estimated using actual field failures.

The final conclusion would be that it is hard to indicate whether reliability prediction can be applicable at Philips Healthcare, since the mentioned problems of collecting data of all indicated factors is not that easy. Other encountered problems like data traceability make creating a prediction model also not easier, but will overcome in time, since people inside Philips are working on some of these issues.
7. Recommendations

In the current chapter recommendations are given, which were stated throughout the master thesis project at Philips Healthcare. Some given recommendations are only applicable for Philips Healthcare others for the research at the TU/e.

Data traceability

The most important recommendation for Philips Healthcare is to provide a good traceability of all data of the systems. Linking the data available to compose the datasets took a lot of time because different departments in Philips Healthcare use their own way of storing data and often their own identification number. Looking from the overall analyses perspective, this can be awkward because no link is clearly visible between the data of the different departments. Philips Healthcare stated already that there are two “official” identification numbers inside Philips Healthcare, but these are apparently not used everywhere. For example, the calls (which call rate is based on) were stored per system by use of ConfigID (configuration identification number). However, this ConfigID number was not clearly used everywhere, and via a long search at other previously unknown databases the systems could be linked. Also should be mentioned that giving one of the two “official” identification numbers is not always possible to do, because the identification numbers concern whole systems, while in some departments also components should be addressed. But if every department adds the universal identification number to their own storage system, this would ease the analyze process, and time is saved.

Data availability

Also in the discussion in the previous chapter, the importance of data was already indicated and suggestions were made. More data available can mean two things:

1. More datasets available for the current set of factors and reliability indicators;
2. More factors available in addition to the current six.

Ad 1. More datasets available means that the neural network has more data to train the network and can add more neurons to the hidden layer to optimize the prediction model. When more AD7 patient tables are in the field, more datasets can be composed. This is just a matter of time. The data for the six factors used and for the reliability indicators from the field can be collected in Philips Healthcare. It is advised to retrain the neural network again when more datasets are available. As is shown in paragraph 4.3, only more call rate date would already increase the current number of data sets.

Ad 2. A lot of factors were not used because of several reasons. In section 4.1.4 is already shown that three indicated factors are not used for modeling only because there was no data available. For the other factors also another reason prevented the factors from being used (see section 4.1.4). Concentrating on these three factors just by collecting more data would already bring more input to the network. However this is not an easy job, but it is recommended for the good of the prediction model. When a lot of factors become available and the datasets do not increase that much, there will be a shortage of datasets in comparison with the new amount of factors. A solution for this could be that the importance of the factors could be estimated. In this way it is possible to select factors from all the available factors. Indicating the
importance of the factors by hand was in the current study not necessary because there were only six factors available.

When more data is available the network can be modeled better. However as is stated earlier, the variance of the data plays also an important role. So when more data is available, but the variance ratio (zero calls per month against some -higher than zero-calls per month) stays approximately the same, this is not an improvement. Therefore it is recommended to take another look to the selection procedure of the call data of the AD7.

Another recommendation considering data of certain factors is that more details should be made available. For example, properties of the patient laying on the table and the user who is giving commands to this table can have influence on reliability. When data is logged of these properties (weight and length of the patient and degree or experience of the user) maybe more relationships could be exposed.

Reliability indicators
Event code rate can also be used for an indicator of reliability of the AD7. Unfortunately this is not yet optimal, because not every system is connected to the RSN network, and systems with event codes can not be linked to the system list which is used to support the datasets. It is recommended to expand the event code rate by upgrading the RADAR system, so that more systems are connected in a traceable way. Only then this output data can be used to support reliability prediction. Another suggestion about the event code rate when more data is available is to look to the description of the event codes, and look for underlying relationships with problems found in the field. This can be done thanks to the software department which make the software in such a way that errors are grouped, indicated by different event codes. In addition to this would be the time of the event code was logged (and not only the day which is the current situation). Also should be investigated whether there is relationship between the instructions or commands given to the AD7 in preceding the occurrence of an error or failure.

When more output data is available about both the reliability indicator, described in the last two text blocs, it is suggested to create a prediction model by using neural network with both the reliability indicators (Call rate and Event code rate). This is an advantage of the neural network method, since it can handle multiple outputs. The model can create a prediction method while using both the output values, which can make the prediction more accurate.

When the above suggestions are (partly) adopted, it is likely that the new trained neural network gives a better outcome with a lower means squared error. However this can not be stated with high certainty, since we do not now for 100% sure that the indicated factors do influence reliability.

As mentioned earlier in this report, it is better to say something about reliability by using MTBF value then by using the indicators used in the current case study. Unfortunately this was not available at the time of the master thesis project, but maybe Philips Healthcare can give an MTBF value of the AD7 in the future when more data is available. This can for example be done counting the replacement parts of the AD7. Parts of the AD7 can contain multiple components. It is recommended to
investigate the components on the replaced part to indicate what the root cause of the failure was.

Another indicator of reliability could be the number of times that an engineer visits a system. A weight for this parameter could then be a gradation what the engineer did. Examples for this could be: only giving a reboot, explaining features to the customer, or replacing whole parts and components.

Reliability indicators
From the results it is known that the data is not linear. However when in the future is found that the data has a monotonic property, it can be tried to use log linear analyses to find relationships with the reliability.

Further research
A recommendation about the approach of the prediction brings us back to the problem analyses (chapter 1) of this master thesis. There is stated that it is best for a product under development that already in the early stages of the PDP an indication can be given about the reliability of the product. This has several advantages concerning time and costs. Probably the best approach to tackle this problem in the situation of the case study is when a new patient table is developed (for example the AD8). Data of the AD7 and maybe the AD5/6 are used to develop a certain prediction model. Because these are all derivative products, this certain prediction model could be used for predicting the reliability of the AD8 by using input data of this new table. Performing a reliability prediction in with these settings, it would be possible to include factors indicated in section 4.1, which can not be used in the current prediction model. A precondition to this method is that the delivered prediction model has an accurate estimation of the reliability of the AD7 and maybe (when available) the AD5/6. Another precondition is that the data which is needed by the model can be (partly) available at the beginning of the new PDP. This is a recommendation for further research for the TU/e and the reliability engineers at Philips Healthcare.
8. Reference


Heckerman D. “Bayesian Networks for Data Mining” Microsoft Research, 95, Redmond. 1996; WA 98052-6399.

Hudson DL, Cohen ME. “Neural Networks and Artificial Intelligence for Biomedical Engineering”. IEEE Press series in Biomedical Engineering; 1999.


Appendix A  Movements of the AD7

Figure 8-1 Cradle

Figure 8-2 Tilt
Figure 8-3 Swivel

Figure 8-4 Close up table
### Appendix B  Complexity of AD7 per configuration

<table>
<thead>
<tr>
<th>Configuration</th>
<th>No. of Movements</th>
<th>Complexity of software mod</th>
<th>No. of Hardware components</th>
<th>Normalized No. of Movements</th>
<th>Normalized Complexity of software mod</th>
<th>Normalized No. of Hardware components</th>
<th>Total complexity ADDED</th>
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- No. of Movements: Number of movements for each configuration.
- Complexity of software mod: Complexity of the software module for each configuration.
- No. of Hardware components: Number of hardware components for each configuration.
- Normalized: Normalized values for comparison across configurations.
- Total complexity ADDED: Total complexity added for each configuration.
## Appendix C  Interviews

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### Brainstorm session 25-1-2008

The idea was to ask one person for every group which is important for the AD7 project, and so hopefully can give an indication of factors that influence the reliability of the patient table. The figure below gives an impression of this idea.

The engineer from Integration & Testing did not attend the brainstorm session because he does not belief he or someone else form his group can give any contribution concerning reliability of the AD7 in the perspective of the “Integration and testing” group.

### Software department

Reliability for software is approximately the same as the state of the quality of the software program. There are always problems in the software ("even NASA has
them”), but a SW problem is only a problem when the user notices that there actually is a problem. The quality issue is concerned with when these problems come out, so in other words the change of occurrence.

Factors from the SW perspective
Factors in the begin phase:
• Engineers’ skills;
• Focus of the project: for the AD7 this changed over time from quality to deliver the products on time.
• New HW platform: this means that a whole new SW part must be written on this HW platform;
• There were no building blocks or modules which the SW group could use from other projects. A problem which comes with this is that they have to test every package/code they made, in stead of using a tested and verified package/code.

Factors in the end phase:
• SW tests;
• Integration tests;
• The number of reviews and the number of comments per reviews.

External factors:
• PC on which software is installed / running;
• Operation System (OS) of the PC (AD7: Windows XP);
• Performance of OS; or e.g. reaction of table with respect to movement of the joystick (<200ms);
• Management.

Field Problem Reports
The Field Problem Reports (FPRs) are used for interaction with user. AD7 problems and/or remarks are reported by service engineers (SE) in the field. Information out of these reports is not used for development (AD7 already in the field). Not every report among the FPRs is reliability issues.

Some non-reliability issues are for example:
• Installation problems: engineer has questions about the installation. Because it is the first time he installs this system and some procedures are new for him, some questions will raise;
• Documentation lacking: not all documentation is clear, or is not properly organized or incomplete;
• Missing functionality: the user wants more or other functionality. A problem which rises here is that the product works according to specification (so it is a non-reliability issue) but the customer expected something else, or thought some certain feature was included in the new design.

Reliability issues among the FPR could be like the ones below:
• Failing of a part / component during time (early wear-out, initial phase of bathtub);
• Decrease functionalities: a certain function does not work anymore, e.g. system does not react.

Reliability & Quality
Like mentioned before, Reliability means according to specifications. In other words, when the products’ functions which are stated in the specifications work correct, the
reliability of the product is good. Even when the customer is not satisfied with the product or when wants something else the product is still reliable. Also reliability is not equal to Quality. The quality of a complex system says something about how the product works; the exactitude of the product.

A lot of FPRs which are now available from the 200 systems in the field are not reliability issues.

Key issues that influence reliability from outside (external):
- Quality of the HW;
- The User itself;
- The user is not aware of problems that influence reliability;
- The end-user point of view;
- E.g. reboot no reliability but it is reliability or the user (dependent on time and occurrence).

**OXB Factory**

People in the OXB fabric are concerned with the design, material and testing of the complex system. In the beginning he said that they needed 21 different configurations, but nobody would listen, saying they had enough with a few less. Afterwards 21 different configurations were made.

The AD7 is a derivative product of the AD5/6. However accept for the bolds and nuts, every part (so every significant part) of the new complex system is different.

The main part of the AD7 was outsourced.
AD7 tested / investigated at application site together with a customer.

Switching from selling / producing AD5/6 to AD7 management planned this as one step. OXB protested from a practical point of view. Because a lot of problems will occur while implementing a complex system, they suggested 3 or more steps, finally it became two steps. So for a period of time as well AD5/6 was sold as AD7.

**Factors from the OXB perspective**

Factors that influence reliability:
- AD7 is part of CV system, look through the users’ eyes;
- Design according to spec: user expectations were different. Conclusion specs were not correctly defined;
- Components;
- External manufacturer of the basic table;
- Error during assembling & error.

First Time Pass Rate is an indication of reliability. This rate was zero at the beginning, this means that there were more then one fault found per system assembled in the factory.

Problems:
- Factory field installers bring limited problems;
- Suppliers bring problems;
• Rocket Movement C2 has more configurations and more functions, so probably more problems.

Service Innovation

Engineer from this department could not make it on the brainstorm session. The engineer is concerned with the speed the service engineers can install or repair a system. They participate in the design phase to make sure a service engineer is able to repair / replace components or panels fast.

The Service innovation department is also involved with the Field Change Order (FCO) process. This concerns HW / SW updates, customer complaints and serviceability complaints.

Reliability vs. Serviceability

Serviceability is not always the same as reliability. Serviceability is the way how a system / customer can be provided the right service. When a problem occurs very often, but the SE is able to solve the problem very fast, the reliability of the system is not very good; however the serviceability is good because of the minimum repair time. On the other hand, when a system has almost never a problem (reliability good) but when a problem occurs, the SE is repairing for a long time, the serviceability is not very good because the customer can not use the product for a long time.

Technical problems usually are product reliability, but when a SE can not fix the problem the service reliability is not good (serviceability).

Factors from service innovation perspective

Factors that influence reliability from the service innovation perspective come out of experience at the department. Experiences of problems of derivative products are noted for the development of a new product. Factors that influence reliability which are found in this department are more related to customers. For example problems with the cabling of the system are already problems for years. Also chairs or other objects can come stuck under the table, and sometimes get crushed. These problems are the fault of the customer not of developer. For a developer it is hard to imagine what a customer can do with the system.

Hardware department

The hardware architect was not able to make it to the brainstorm session; this is way he is interviewed a week later.

The FMEA which is made by CV around the AD7 is too technical for the viewpoint of the service innovation department.

Reliability of the hardware is preserving the quality in time, and whether the system is according to spec. because there are only a few (relatively) on the market for less than a year, nothing can be said about the reliability.

• Infant problems
• Quality issues are solved first
• Product must be longer to market before being able to say something about the reliability.

Factors that influence reliability

Factors that can influence reliability from the hardware perspective are:
• The number of components
The reliability of each component of the system separately
Out of experience it is known how to use certain components in the system (because of experience with derivative product, AD5), however in the AD7 more components are implemented which makes this system more complex.

Calibration errors are more design faults / issues, because the HW and the SW might be good, but because in the design a mistake is made, the calibration of a component could be wrong. This problem could slip through tests and only noticed in the factory. But a wrong calibration could be a reliability issue, because the product does not (always) according to spec.

Factors from general view
Factors that influence reliability that were designated by all attendees were:
Education of the user. The user must be properly prepared by training or course so that he knows what to expect from the system and know how to use the system. In this way fewer questions about the system will arise. Giving training is a part of the service innovation department. (Measure level of training use for factor)
Training maintenance. Training engineers how to install the system, and later also how to conduct preventive maintenance will prevent problems for the engineer and so customer;
Complexity of the system:
The number of parts;
The number of movements (degrees of freedom);
Wiring;
Software linear;
Combination with the C-part (the arc).

Conclusion of the brainstorm session
No specific levels of factors could be given by the attendees. However confirmation for the factors that influence reliability which were uncovered during earlier interviews was given.
### Software event codes

#### Table 8-2 Part of all Event codes for the AD7

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<tr>
<th>Event Code</th>
<th>Description</th>
<th>Solution</th>
</tr>
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<td>AMC drive interface failure</td>
<td>Software problem, send logging to helpdesk.</td>
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<td>I2C interface failure</td>
<td>Check I2C device on height axis drive.</td>
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<td>Check MOTION CONTROL BOARD + drive + SynqNet Cabling.</td>
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<tr>
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<td>Hardware not present or defect</td>
<td>Check / Replace Motion Control Board.</td>
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<td>63001008</td>
<td>Motion not disabled in time axis</td>
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<td>recovered</td>
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<td>Table power is switched off</td>
<td>This usually has is caused by a safety related issue that occur before.</td>
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<td>POST: Axis not in stopped state</td>
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<td>MPIEventTypeLIMIT_HW_NEG</td>
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<td>Frame buffer underflow</td>
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<td>SynqNet failure</td>
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<td>Application error: SynqNet info</td>
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<td>mpiControlReset failed</td>
<td>Restart system, if persists replace Motion Control Board.</td>
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<td>Move to start position first.</td>
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<td>recorded move</td>
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<td>63001025</td>
<td>Drive error: Internal fault</td>
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<td>63001026</td>
<td>Drive error: Short circuit</td>
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### Table 8-3 Sample of data sets of total 306 AD7 Patient tables

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Appendix F  Theory behind Neural Networks

In this chapter the theory behind Artificial Neural Networks (further referred to as Neural Network or NN) will be discussed. Also an indication will be given to what kind of data is needed to use a NN for reliability prediction.

**General**

By the use of Neural Network models solutions are found to approximated problems instead of approximating solutions of exact problem formulations (Hudson and Cohen, 1999). Neural networks allow rapid development of a model through the learning algorithm if sufficient data are available. In more practical terms: neural networks are non-linear statistical data modeling tools. They can be used to model complex relationships between inputs and outputs or to find patterns in data (Du and Swamy 2006).

It is estimated that the human body contains approximately 100 billion neurons. Neurons are information- and signal-processors in the human body. An important characteristic is that they can receive and pass on signals. In the human brain circuits of these neurons exists which regulate a lot of vital body functions, and are also responsible for our intellect. Traditionally, the term Neural Network referred to this network of biological neurons in the human body.

Neural network is proven to be suitable for reliability prediction (Karunanithi et al., 1992). The network only requires the failure history as input and no assumptions. The model automatically develops its own internal model of the failure process and predicts future failures (Karunanithi et al. 1992). However this depends strongly on the available data.

To get a better insight in Neural Networks, in the next sections the structure and properties of the Neural Network will be discussed. First the neuron will be discussed and some basic rules for using them. The general architecture of the network will also be presented. Finally, some learning rules for a network will be discussed.

**The neuron**

The basic idea behind neural networks is to construct artificial neurons that have the characteristics of actual neurons (Hudson and Cohen, 1999). The neuron is the most important element in a NN. According to its input value(s) the neuron determines what the output value of the neuron will be. Neurons receive input from (multiple) other neuron(s) or input parameters. In Figure 8-5 simple neuron is shown. A simple neuron has the same operating standard as conventional computers; there is no improvement with respect to earlier computational programs. A simple neuron is not self thinking; it just does what it is told to. A more sophisticated neuron is shown in Figure 8-6 which is the McCulloch and Pitts model (MCP). This neuron has weighted inputs, which makes the neuron more useful.
These weights are part of the connections between neurons. The connections are called synapses or connecting links (Haykin, 1994). The weights indicate the importance of the relations between the neurons. A high weight value means that the predecessor neuron has more influence on the following neuron than a lower weight value. The neuron makes, on basis of the multiple inputs (either positive or negative weights), one output value.

Several neurons together form a neural network. The structure of this is discussed in the next paragraph.

**The architecture**

A very common neural network nowadays is shown in Figure 8-7. It shows the architecture of a simple feed-forward backpropagation neural network. Feed-forward networks were the first and simplest NN. Backpropagation is an abbreviation of backwards propagation of errors. On the left-hand side the network starts with its inputs. The neurons (the circles in the figure) are connected by synapses. On the right-hand side the output of the network is shown. A more elaborate description of the network is given below.
**Input layer**
The first layer (i.e. the first layer in Figure 8-7) is called the input layer and exists out of several neurons which get their information from one or more input parameters. To handle the different requirements the amount of neurons in this layer can be varied.

**Hidden layer**
The second layer also consists of a set of neurons, which are connected to the neurons of the preceding layer. A NN may contain one or more hidden layers. Each hidden layer may contain a different number of neurons. A NN for a very complex system may need more hidden layers to enclose the whole system. Normally one hidden layer is best for the network, since it becomes unmanageable.

**Output layer**
The output layer contains as much neurons for the output as is wanted by the constructor. However usually one neuron is sufficient. The neurons of this layer are connected to the neurons of the adjoined hidden layer. This output layer provides the response of the network.

The synapses (the connections between neurons) have a certain weighted factor. These factors get modified during the training process. Every neuron in the network has its associated bias (see Figure 8-7) which adjusts the output of each neuron. The bias can be changed during training and always has influence on the output value of a neuron. More neurons in the hidden layer require more computation, but allow the network to solve more complicated problems. Increasing the amount of neurons will increase the network’s performance up to a certain point (Adnan et al., 2000). More layers require more computation, but might result in the network solving complex problems more effectively.

Every neuron in the network has a transfer function that determines its output. The principle of transfer functions is discusses in the following section.

**Transfer function**
The output of each neuron is determined by its weight, bias and the transfer function which is associated to that neuron. A transfer function determines the outcome of the neuron according to the input. The transfer functions can determine the output of a neuron in different ways (Figure 8-8 Neuron with Transfer function).

![Figure 8-8 Neuron with Transfer function](image)

The transfer function typically falls into one the following three categories (Rajpal, 2005):
- Linear: the output value is set according to the total weighted output value. A very familiar linear transfer function is Purelin;
Threshold: the output value is set at one of two levels. This depends on whether
the input value is higher or lower than the threshold value;

Sigmoid: the output value varies continuously as the input changes. The mostly
used sigmoid transfer functions are Tansig (Hyperbolic Tangent Sigmoid) and
Logsig (Log-Sigmoid).

There is no golden rule which transfer function should be taken. Each neuron can
have its own transfer functions. In the case of reliability prediction, a Sigmoid transfer
function is the most useful, however it is common that by trial and error the best
function is chosen (Rajpal, 2005).

Before a network of neurons is useful, it must be trained; in order to know what kind
of value the outputs of the neurons should be when a certain input pattern is given.

Training a Neural Network

The purpose of the NN is to minimize the output error by adjusting network vector-
weights and biases. These values will be adjusted by learning / training the network
(Yao, 1999). In other words, learning or training is an optimization process that
produces an output that is as close as possible to the desired output by adjusting
network parameters (Du and Swamy, 2006). This kind of parameter estimation is also
called learning or training algorithm. The backpropagation algorithm is used
extensively in neural network applications (Rajpal et al., 2005), because it is the
simplest and most straightforward method.

Neural Networks are usually trained complete runs when all the training examples are
presented to the network and are processed using the learning algorithm only once.
This complete run is called epoch. (Du and Swamy, 2006). Thus the network learns
outcomes which belong to certain input patterns. It also learns what output to give
when a portion of a pattern is given, or when the given pattern is distorted. This
makes NN suitable for situations with incomplete data.

Also the network can store pairs of patterns to build an association between two sets
of patterns. Some networks have fixed weights, which are preset to solve a specific
problem. Adaptive networks on the other hand are able to change their weights.

Learning methods for neural networks are divided into four categories. Each of the
four categories has their own application(s) (Du and Swamy, 2006):

- Supervised learning is widely used in pattern recognition, approximation, control,
modeling and identification, signal processing, and optimization;

- Unsupervised learning schemes are mainly used for pattern recognition,
clustering, vector quantization, signal coding, and data analysis;

- Reinforcement learning is usually used in control;

- Evolutionary learning is used for adjusting NN architecture and parameters using
an evolutionary algorithm, and can also be used to optimize the control parameters
in a supervised or unsupervised learning algorithm.

Because for the current case study data optimization and modeling and identification
is needed, supervised learning will be more elaborated below.
**Supervised learning**

This method of learning is based on a direct comparison between the actual network output and the desired output. The network parameters are adjusted by a combination of the training pattern set and the corresponding errors between the desired output and the actual network response (Du and Swamy, 2006).

Supervised learning with examples of input-output pairs is used for training which are provided by the algorithm. The training begins with random weights and biases. These weights and biases are adjusted by the algorithm for minimizing the errors. There are several standard algorithms, but there is no single algorithm that solves all problems. The overall strategy which is used is to experiment with several of these training algorithms. Then locate the most suitable one for the given application (Rajpal et al., 2005). An important issue concerning supervised learning is the problem of error convergence. The output will be converged to a local minimum in a neighborhood of the initial solution of network parameters. In this way a set of weights which minimizes the error will be found.

**Dataset**

To train the neural network, datasets are needed. The training sample comprises the data records used to train the neural network; some percentage of cases in the dataset must be assigned to the training sample in order to obtain a model. The testing sample is an independent set of data records used to track errors during training in order to prevent overtraining. Network training will generally be most efficient if the testing sample is smaller than the training sample. The validation sample is another independent set of data records used to assess the final neural network. The error for the validation sample gives an “honest” estimate of the predictive ability of the model because the validation cases were not used to build the model. In some cases it can be a problem that the NN demands a lot of data to model properly. The most used distribution of the available data sets are 60% for training, 20% for testing and another 20% for validation of the network.

**Number of neurons**

The input layer has as many neurons as that there are input parameters. The output of the network (the output layer) exists out of as many output neurons as there are available. So the structure of a dataset determines the number neurons in the input and output layer. The amount of neurons in the hidden layer depends on the size of the dataset. It is suggested in literature that the best way to find the right amount of neurons in the hidden layer is by trial and error. A heuristic for the amount of neurons in the hidden layer is 10 datasets per synapse (Zhang et al. 1990). But it is stated that more datasets is better for the performance of the network. Another general rule of thumb is to determine the number of hidden units as the half of the total input and output neurons.

A disadvantage of the NN is that it is a “black box” model. Because of this it is very difficult to get an inside in the model, in contrast to regression modeling, where coefficients already give an indication of the relationship. Software programs do give an importance level of parameters used as inputs for Neural Network, but the real relationship stays hidden.
### Appendix G Event Codes Correlation

| Use | Fault | Hard | Com | Purp | Regio | Call | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 18 | 19 | 26 | 27 | 28 | 44 | 46 | 47 | 51 | 52 | 54 | 63 | 64 |
| Use Profile | Pearson Correlation                      | Sig (2-tailed) | 0.99 | 0.90 | 0.96 | 0.87 | 0.69 | 0.61 | 0.60 | 0.59 | 0.58 | 0.57 | 0.56 | 0.55 | 0.54 | 0.53 | 0.52 | 0.51 | 0.50 | 0.49 | 0.48 | 0.47 | 0.46 | 0.45 | 0.44 | 0.43 |
| Faults in OXB version | Pearson Correlation                      | Sig (2-tailed) | 0.87 | 0.78 | 0.71 | 0.63 | 0.55 | 0.47 | 0.46 | 0.45 | 0.44 | 0.43 | 0.42 | 0.41 | 0.40 | 0.39 | 0.38 | 0.37 | 0.36 | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.30 | 0.29 |
| Complexity | Pearson Correlation                      | Sig (2-tailed) | 0.80 | 0.71 | 0.63 | 0.55 | 0.47 | 0.39 | 0.38 | 0.37 | 0.36 | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.30 | 0.29 | 0.28 | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 |
| Purpose of use | Pearson Correlation                      | Sig (2-tailed) | 0.75 | 0.66 | 0.58 | 0.50 | 0.42 | 0.34 | 0.33 | 0.32 | 0.31 | 0.30 | 0.29 | 0.28 | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.20 | 0.19 | 0.18 | 0.17 | 0.16 |
| Regions | Pearson Correlation                      | Sig (2-tailed) | 0.70 | 0.61 | 0.53 | 0.45 | 0.37 | 0.29 | 0.28 | 0.27 | 0.26 | 0.25 | 0.24 | 0.23 | 0.22 | 0.21 | 0.20 | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 |
| Call Rate | Pearson Correlation                      | Sig (2-tailed) | 0.65 | 0.56 | 0.48 | 0.40 | 0.32 | 0.24 | 0.23 | 0.22 | 0.21 | 0.20 | 0.19 | 0.18 | 0.17 | 0.16 | 0.15 | 0.14 | 0.13 | 0.12 | 0.11 | 0.10 | 0.09 | 0.08 | 0.07 | 0.06 |

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