MASTER

# Improving reliability control through testing
a research study at Philips DAP-Shaving

Timmers, A.A.J.

*Award date:*
2006

# Improving Reliability Control through Testing

*A research study at Philips DAP - Shaving*

Master Thesis
A.A.J. Timmers
April 2006

TU/e technische universiteit eindhoven

PHILIPS

TU/e technische universiteit eindhoven

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**Author**

**Name** A.A.J. Timmers
**Student ID** 475713

**Supervisors**

**1st supervisor** Prof. Dr. Ir. A.C. Brombacher

Eindhoven University of Technology
Faculty Technology Management
Section Quality and Reliability Engineering

**2nd supervisor** Dr. Ir. P.H. den Ouden

Eindhoven University of Technology
Faculty Technology Management
Section Quality and Reliability Engineering

Philips Applied Technologies, Eindhoven

**Philips supervisor** E. Boom

Reliability Engineer
Philips DAP, Drachten
Development Quality Department - Shavers

# Abstract

In order to compete in the market, companies have to produce the right products with a shorter time to market and at lower costs than before. Shorter time to market requires the product creation process (PCP) to change the way of working. Instead of the classical 'wait and react', problems should be anticipated and prevented as early as possible in the development process. This requires a different role for the Development Quality Department (DQD) of Philips DAP. This thesis discusses the use of reliability tests to control the reliability of a design, during the different phases of the PCP.

# Acknowledgements

This report is the end result of an eight-month graduation project executed at the Domestic Appliances and Personal Care Division of Philips Electronics N.V. located in Drachten. The project was the final phase of my study in Industrial Engineering and Management Science at the Eindhoven University of Technology.

This graduation project would not have been possible without the support and supervision of several people. Therefore, I first want to thank my supervisors from TU/e Aarnout Brombacher and Elke den Ouden. Thank you for keeping me on track, giving useful input and giving me the opportunity to finish this project. Then I want to thank Evert Boom my daily supervisor from Philips DAP for this opportunity to gain experience in a multinational company as Philips and of course all other people at the development quality department for making me feel so welcome as a 'Zeeuw' among the 'Friezen'.

Thirdly, I want to thank all current and former inhabitants of 'Huize Moio' for giving me an unforgettable period as a resident of the city of Groningen. Finally, I would like to thank my family and friends who did not forget me and encouraged me whenever I needed it.

# Executive Summary

## Introduction

This research study was conducted at Royal Philips Electronics N.V. Philips started about 1891 as manufacturer of light bulbs. Meanwhile, Philips is one of the world's biggest electronics companies and Europe's largest. Philips produces a wide range of products for a wide range of customers and is active in about 100 businesses in over 60 countries. It has market leadership positions in medical diagnostic imaging and patient monitoring, colour television sets, lightning, silicon system solutions and electric shaving. The actual setting of this research study is the Development Quality Department (DQD) of Philips Domestic Appliances and Personal care (DAP) in Drachten. The responsibilities of this department can be subdivided into two parts:

- First the DQD is responsible for product, module and component release based on both the Product Creation Process (PCP) and the Function Creation Process (FCP). During the different phases of these processes the product, module or component are tested and finally the DQD gives the advice to release the design.

- The other responsibility of the DQD is to collect, analyse and classify data from the field and from mass-production in behalf of corrective actions for production and preventive actions in behalf of development and projects.

The research study started with a fairly broad problem description:
***"Changes are the order of the day. The success of the company is therefore linked more and more with the ability to flexibly implement conformations to these external and internal changes. At this moment the DQD receives many signals that ask for a different approach regarding the control of quality and reliability of the shavers developed in the PCP of Philips DAP. Strategic considerations herewith are 'speed' and cost reduction [Phi05]."***

To come to a well-defined research objective first the trends dominating the market and their consequences and requirements on the business process are discussed.

## Research Context

In 1939, the first Philishave model was brought on to the market, a simple cigar-shaped, one-headed shaver with a bakelite body, directly connected to the mains. In the mean time, it has evolved to a high-volume market with a great variety of products. At the moment the high-volume consumer industry is dominated by four major trends. These trends are: the decreasing time-to-market, the increasing product complexity, the globalisation and segmentation of business processes, and the changing role of the customer.

As a result of above trends manufacturers of high-volume consumer products are under pressure, because there originates a conflict between their four most important business drivers. These business drivers are:

- ***Functionality:*** is the product able to fulfil its intended function.
- ***Time:*** does the product reach the market at the required moment.
- ***Profitability:*** is the difference between product cost and product sales price adequate.
- ***Quality/Reliability:*** does the product fulfil customer requirements at 'all' customers, not only at the moment of purchasing but also during operational life of the product.

Manufacturers of high-volume consumer products are confronted with a situation where:

- The high innovation speed puts pressure on the time to market
- Customers require excellent product quality and reliability

The Product Creation Process (PCP), from product idea up to and including after sales service, must cope with these requirements. To satisfy these requirements there has been a shift from a functionally structured PCP to a PCP structured according to the principles of concurrent engineering.

In adapting to these trends, the functional PCP is limited by two assumptions. First, there is the assumed interdependency pf the individual functions. However this disregards the fact that decisions in the early phases of the PCP can seriously affect the performance of the later phases of the process. The second loss is the assumed time-independency of decisions. Yet, changes in later phases require far more time and money than changes performed during early phases. To deal with the previous conditions there has been developed a different structure; Concurrent Engineering. The idea behind concurrent processes is that downstream activities start as early as possible, even when upstream activities have not been completed. The use of concurrent PCPs puts strong demands on the predictive capabilities within a development process. Besides finding and solving known problems, a concurrent PCP has to be able to predict and prevent all potential problems.

These changes in the PCP do also have a major impact on the two main responsibilities of the DQD of Philips DAP.

## Problem description

A long time ago the development process was simple and the interaction between the client and the manufacturer was very intense in those days. Since the introduction of mass production, the interaction between the client and the manufacturer has become rather indirect. For mass products normally the only contact takes place when the client has a problem with the product and contacts a service centre (SC). Nevertheless, in order to improve product quality/reliability, the use of field information is essential. Depending on the goal, different kinds of information in the flow from the field are relevant.

When the feedback flow of Philips DAP is observed a number of points stand out. In the first place, Philips DAP has a substantial advantage having a SC at the Drachten plant. Thus failed products with new unknown failure modes can be examined by the person/team that developed the failing part of the shaver. However, the feedback cycle also has its weaknesses. The metric used to express product performance on the market, the Field Call Rate (FCR), is a very slow metric and is useless for close monitoring of the field behaviour of products. The FCR is only helpful as a comparative number, it then strikes that the FCR of High-End (HE) innovative shavers with a number of new technologies is up to three times as high as the FCR of Medium- and Low-End shavers that use proven building blocks and known technologies. Besides there exist very long delays between production of the shaver, sales and failure report. So a large number of bad appliances can come on the market before the failure is detected and repaired. Another weakness is that not all available feedback information is used for root-cause analysis (both technical as organisational). The feedback loop is not always closed and design changes are made before the exact origin of a failure is known. Therefore it gets more and more important to find all quality and reliability issues yourself.

A classical test satisfies the ability of the product to meet its specifications. This way of working only is effective when no uncertainties do exist. In this case it is possible to write a complete set of technical specifications that can form the limits of control charts to control design quality and reliability. This causes, however, a direct conflict with the concurrent PCP because in such a process potential problems, found normally during product tests, should have been identified already during the earlier phases of product development. Therefore, in concurrent PCPs two classes of tests can be identified. The first class consists of validation tests. Like the classical tests, these are aimed at confirming the performance of the product. The second class consists of analysis tests. An analysis test is a test where potential critical aspects of a product are tested early in the PCP. The test is 'failure oriented' and aimed at confirming or rejecting risks that may or may not happen in a future product.

The test program of Philips DAP is found upon more than 60 years of experience. This experience is recorded in the General Test Specifications Shavers (GTSS). However, due to the high innovation speed on the contemporary market of high-volume consumer products the number of different tests keeps growing to unmanageable proportions resulting in high costs. Besides, almost all of the tests in the GTSS are classical validation and verification tests that test if the product meets its specifications. These tests are executed when a larger number of prototypes come available about halfway down the PCP. This way of working satisfies for products that use proven technologies for familiar users, but is not suitable for innovative products that bring about lots of uncertainties. In that case there is a need for analysis tests early in the PCP to reduce these uncertainties and confirm or reject risk that may happen in a future product. It therefore is a challenge how to do such failure-oriented analysis tests.

## Research methodology and research questions

The above results in the main research question.

***"How can failure-oriented analysis tests be executed in the early phases of the PCP of Philips DAP that are able to find all design errors and weak links in a design?"***

To answer this question it is important to know why failures that come up on the market at the customer are not detected in the current test program. Therefore first a real market failure was selected and examined to answer the following questions:

- ***"In what way can available feedback information be utilised better to analyse failure mechanisms and identify relevant sub-populations of extreme users/products?"***

- ***"What is the technical root-cause of the selected failure and how can it be reproduced in a test environment?"***

- ***"What is the organisational root-cause of the selected failure?"***

## Literature

From a customer point of view the principal reason to report a (reliability related-) complaint is that, at a certain moment in time, there is a mismatch between customer requirements and the product performance. Although from a customer perspective all instances of such a mismatch will be grouped under the denominator 'Reliability Problem' there can be a large number of, fundamentally different, processes leading to such an event. This research concentrates on physical failures. In the case of physical failures it is assumed that a product consists of components and that a failure happens when a (physical) gradual or instantaneous change occurs in a component. The process resulting in a failure is called the failure mechanism. A failure mechanism is influenced by one or more stressors, which is a physical entity influencing the lifetime of a component or circuit.

As already observed earlier, for a time-driven PCP, analysis test are required to optimise product design. A classical solution is to use accelerated stress testing (AST) to find reliability problems already during the early phases of product development. Accelerated testing is a method to activate product failures faster and cheaper in a well-controlled environment at the early stages of the PCP. There are two common principles that can be followed to speed up the failure mechanisms. These strategies are: increased probability of extreme stress and increased level of extreme stress.

The classical AST tests products according to a commonly accepted standard/generic list against the constant failure rate model. The use of a generic list to conduct AST has a number of known risks. It could be possible that unrelated failure mechanisms might be activated, irrelevant stresses might be used, or test results might be interpreted wrongly without the knowledge of the genuine failure mechanisms that may happen in the field. That is, classical AST only tests for the constant failure rate with poor correlation to the actual product field performance. Next to this classical AST strategy there are some very recently developed AST strategies, i.e. Highly Accelerated Stress Test (HAST), Multiple Environment Over Stress Test (MEOST). However it was observed that all AST strategies use generic lists and there is lack of distinct knowledge of failure behaviour of (sub-) populations of products. The use of such AST strategies lead to low predictability during the early stage of the PCP because irrelevant failure mechanisms may be tested under irrelevant stress profiles and test results may be misused to predict the product field performance. From the foregoing it can be concluded that the classical AST strategies do not correspond with the failure mechanisms that arise in the field. A naturally arising alternative to the classical AST that tests the product against failure mechanisms identified from the analysis of the physics of the field failures. This strategy is called 'Physics of Failure' strategy. It requires the knowledge of the relevant failure mechanisms, product susceptibility, product specifications, interaction between different failure mechanisms, etc. Keeping in mind, not all users are the same resulting in different stress levels, not all products are the same so strength is product related and even if all products would be the same then not all products would remain the same. Therefore when performing AST a different strategy should be applied for each of the four phases of the roller coaster curve.

In any design in which performance, reliability or durability might be affected by variations they must be included in the test program. If only one or a few variations are considered likely to have significant effects, the effects are understood, and there are no interactions between them, then conventional one-at-a-time tests using the AST strategies might be sufficient. However if these assumptions cannot be safely made, then statistical experiments should be performed to determine which variations and interactions are significant, what the causes of the variations are and how variation can be reduced. The most powerful of the techniques to set up such statistical experiments is called the Design of Experiments (DoE). DoE is particularly important in two areas:

1. For resolving chronic quality and reliability problems in production and in the field
2. At the design stage of both product and process

## Root-cause analysis; an experimental research

Now a real market failure is selected and examined more closely. First all available feedback information is gathered and mapped according to the principles of DoE. Thus the unmanageable large number of potential influencing stressors and variables is reduced. Based on this analysis it can be concluded that there is no matter of weaker sub-populations of the product. But we have to do with a time-dependent failure potentially present in all products of this particular shaver family. Therefore the explanation for the fact that some customers do suffer from this specific problem and other do not must be found in variations in customer use. And the failure can be classified as a phase 2 early wear-out problem.

Now the failure has been classified and the number of potential causes has been reduced, the product is tested according to the PoF approach for phase 2 failures. The failure mechanism is accelerated both by increasing the probability of extreme stress and by increasing the level of extreme stress. This strategy resulted in replication of the market failure in a fraction of the time-to-failure observed in a market situation. And the analysis showed that a combination of DoE and PoF based accelerated stress testing is a successful approach for the root-cause analysis of market failures. Subsequently the possible follow-up actions are described.

After this technical root-cause analysis the organisational root-cause of the failure is determined. Why is this particular failure not found during the current test program in the current PCP structure? The answer to this question is dual. First, the most important stressor accountable for the occurrence of this particular failure is not included in the current tests. And the design of the failing part has been changed without considering all possible results. Resulting in the following two additional requirements for the analysis test:

- *Tests are developed exclusively for a certain design: the design is exposed to all conditions that induce a risk for failing of that design in the market.*

- *Also relatively small design changes can effect the reliability of a (sub-)design, therefore the influence of a particular design change should always be taken into consideration*

## Proactive reliability control; analysis testing

To determine what aspects of new developed shavers need to be reviewed in early analysis tests, the strategy used can be described as the inverse of the Maturity Index on Reliability (MIR). It starts with a new or changed design or for a different market segment bringing about uncertainties regarding reliability. Subsequently it should be predicted what the possible failure mechanisms are for this new or changed design. Then based on the outcome of the analysis tests, the potential effect of these failure mechanisms on sub-system behaviour should be predicted, eventually leading to an estimation of the product behaviour on the market. When this outcome is insufficiently the design needs to be changed and tested again.

Next, the activities and organisation around proactive reliability control through analysis tests were discussed. To structure the different test activities, these activities have been dealt with following a Plan-Do-Check-Act (PDCA) cycle. A PDCA cycle is a continuous quality improvement cycle that can be used at several levels, strategical and operational. The definitions of plan, do, check and act that have been used are:

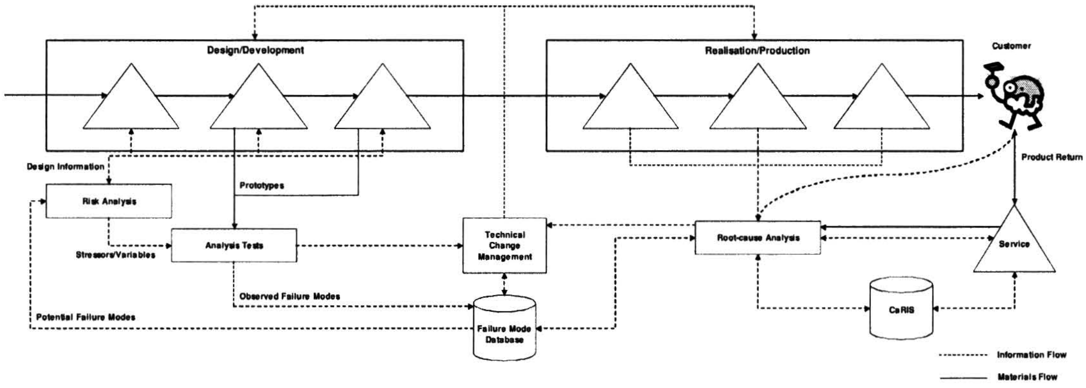
- **Plan:** Preparation of the test
- **Do:** Execution of the test and collection of data
- **Check:** Assessment of the test results, is design improvement necessary?
- **Act:** If necessary, make design improvements.

Making use of this PDCA-cycle a working method for analysis tests was discussed in more detail. Using this working method, decisions can be made on who, what, why and when for the test in the future.

## Conclusions and recommendations

The aim of the research was to study how product reliability can be controlled better by doing the right tests at the right moment in the design process, providing the right information for design optimisation. The general conclusion of the research is that the feedback reliability control will improve by: 1) Using DoE-tools to analyse the available feedback information of market failures; and 2) Using PoF based accelerated testing to replicate these market failures. And that the feedforward reliability control in the design process will improve by: 1) Using a risk analysis as an input for analysis testing; 2) Searching for the weak links of design by executing PoF based AST based on this risk analysis, throughout the design process; 3) Starting with the identification of potential reliability problems at the earliest stages of the design process.

This is schematically summarized in the following figure:



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# 1 Introduction

The contemporary product development process is influenced by a number of trends that can be perceived in the present-day industry. These trends, such as increasing product complexity and increasing pressure on time-to-market, demand better organised product development processes. These product development processes should eventually bring forth products that are first time right, according to specifications, but at the same time matching the expectations of the customer in every way.

To assure such a high quality level, it is of great importance that a company has the right information at its disposal, at the right time, at the right place, to take the right decisions. By anticipating on this required information, unnecessary risks when launching a new product can be avoided. This challenge also affects the processes within Philips DAP Shaving. This study will therefore focus on the information necessary to reduce these risks.

In this first chapter a short introduction to the research will be given, starting with a description of the company where the research was executed. Next, the product and its market will be covered and the chapter closes with the initial problem description as formulated by Philips DAP.

## 1.1 The Company

Royal Philips Electronics is one of the world's biggest electronics companies and Europe's largest, with sales of € 30.3 billion in 2004. With activities in the three interlocking domains of healthcare, lifestyle and technology and 161,500 employees in more than 60 countries, it has market leadership positions in medical diagnostic imaging and patient monitoring, colour television sets, electric shavers, lighting and silicon system solutions. Philips spends over 10% of its sales revenues on Research and Development, and strives for technological leadership.

Philips has five main divisions: Philips Consumer Electronics, Philips Lightning, Philips Medical Systems, Philips Domestic Appliances and Personal Care and Philips Semiconductors. The four main consumer regions that are served are: Latin America (LATAM), Europe (EU), Asian Pacific (AP) and North America (NAFTA).

This assignment has been carried out at one of the five Business Units (BUs) belonging to Philips Domestic Appliances and Personal Care (DAP). Philips DAP produces a wide range of products to help people prepare healthy food and beverages, care for their home and garments, and enhance their beauty and sense of well being - in short, it makes products that improve the quality of people's lives. Philips DAP is a marketing-led company focusing on healthcare, lifestyle and technology. One of the core competences of Philips DAP is the formation of strategic partnerships with other companies, which has brought forth for example the Senseo coffee machine with Douwe Egberts and the Cool Skin shaver in co-operation with Nivea. Philips DAP is a large organization with a strong global presence. It has manufacturing operations in seven different countries and national sales organizations in 45 countries. It employs some 8.000 people worldwide. In 2003, the division's sales amounted to € 2.131 million, while its income from operations was EUR 398 million, figures that make DAP one of Philips' most successful and profitable divisions.

Philips DAPs activities are grouped into five Business Units (BU's):

- Shaving & Beauty
- Oral Health Care
- Food & Beverage
- Home Environment Care
- Consumer Health & Wellness

Philips Shaving is a so-called Line of Business (LoB) within the business unit Shaving & Beauty (S&B) that develops and manufactures electric shaving products. Philips Shaving is the global leader in male dry shaving since 1939. Philips DAP Drachten, designs electric shavers, the necessary production and assembly lines and produces them. A second production site is the manufacturing plant in Zhuhai, China. For the rest of this thesis, where 'Philips DAP' is used it refers to the Shaving division at Philips Domestic Appliances and Personal Care Drachten, The Netherlands. Within Philips DAP three main processes and five supporting processes are defined (Appendix A).

This research was executed at the Development Quality Department (DQD), which is part of the Innovation Process. The objective of this innovation chain is: **to deliver a continuous flow of new shaver families that are attractive and trendsetting to the trade and end-users, that fit into the industrial structure of Drachten / Zhuhai and that will fulfil the financial targets of the BU S&B.** The place of the innovation process in the business and its structure with its in- and outputs are schematically represented in Appendix A.

## 1.2 The Product and its Market

The product created at the LoB Shaving at Philips DAP is the Philips/Norelco (US) electrical shaver, formerly known as Philishave. An electrical shaver is a rather complex product because it consists of both an electrical part as well as a mechanical one. Philips DAP divides its product range into three different categories: dry (2- and 3-headed), washable (2- and 3-headed) and additive shavers (Cool Skin). Inside these categories there is further differentiation in low- and high-end product series. Such a product series is built of different models, which have the same design and main functionalities but differ in battery type, number of LEDs, colours and accessories.

Within Philips DAP the development strategy of downgrading is practised. Downgrading implies that a new shaver will replace a shaver in the High-end segment, next specific technologies or sub-assemblies of this particular older shaver will be used in a new Medium-end shaver. This shaver will replace an older Medium-end shaver, which could be downgraded as well.

The main architecture of these shavers however shows great similarity. An example of the exploded view of a shaver and the matching parts list are given respectively in Appendix B and C. Each shaver minimally consists of a shaving-head, driving-unit + motor, power-supply and cover.

The market for electrical shavers was a relatively stable and mature market. It has however changed into a fairly dynamic market in which innovations are rapidly followed one after another. The market volumes in Western Europe and in the USA are remaining almost constant. Only in China and a number of other Asian countries there is room for market growth, in 2004 about 23% in value and 25% in units. Philips is the market leader in electric shaving in Western Europe as well as in the USA and in China. Its most important competitors are Braun and Remington in Western Europe and the USA and Braun and Panasonic in China and Asia.

## 1.3 Initial Problem Description

As mentioned, this graduation project was mainly executed at the development quality department (DQD) that is part of the innovation process. The activities that are performed by the DQD can roughly be divided into two parts:

- First the DQD is responsible for product, module and component release based on both the Product Creation Process (PCP) and the Function Creation Process (FCP). During the different phases of these processes the product, module or component are tested and finally the DQD gives the advice to release the design.

- The other responsibility of the DQD is to collect, analyse and classify data from the field and from mass-production in behalf of corrective actions for production and preventive actions in behalf of development and projects.

This research started with a fairly broad problem description:
***"Changes are the order of the day. The success of the company is therefore linked more and more with the ability to flexibly implement conformations to these external and internal changes. At this moment the DQD receives many signals that ask for a different approach regarding the control of quality and reliability of the shavers developed in the PCP of Philips DAP. Strategic considerations herewith are 'speed' and cost reduction [Phi05]."***

In order to arrive at a well-defined research objective, in the following chapter the trends dominating the market as well as their consequences and requirements on the business process will be discussed. Main emphasis will go to quality and reliability control by testing and field feedback information. In chapter 3 the current situation at Philips DAP and the DQD will be analysed based on the preceding context review from chapter 2. Subsequently the insights gained from both chapter 2 and 3 will be combined to come to a clear-cut research objective in chapter 4.

# 2 Research Context

## 2.1 Effects of Trends

In 1939 the first Philishave model was brought on to the market, a simple cigar-shaped, one-headed shaver with a bakelite body directly connected to the mains. In the meantime it has evolved to a high-volume market with a great variety of products. At the moment there are four major trends that dominate the high-volume consumer industry. In the following subparagraphs these trends are discussed.

### 2.1.1 Increasing product complexity

There is an increasing complexity of products; this means that the products must have an extended functionality, more functions with a better overall performance. For shavers this first of all means improving the closeness of shaving with less skin irritation and more comfort. Recent innovations are the introduction of the additive shavers, personal comfort control, LCD/LED-displays, more advanced embedded software and also even a washing machine for the shaver. It is a challenge for companies to control the reliability of these more and more complex products [Luy02], [Pet03].

### 2.1.2 Changing role of the customer

A second trend is the changing role of the customer. Consumers tend to be satisfied only if the product they bought suits their particular demands and needs. If a product works according to specification, but does not meet the expectations the consumer has of the product it leaves the customer dissatisfied and probably a customer is lost to a competitor. Coherent to this is the fact that the warranty policy shifts from a strict policy to a 'no-questions-asked' policy. This means that an unsatisfied customer can return his product without a specific reason. Also the warranty times increases from one year to two years or even three years [Luy02], [Pet03].

Several years ago Philips DAP upgraded its warranty period on shavers from 1 year to 2 years. At the moment there is some research running about what the effect would be if the warranty period would be extended to 5 years. Another change in the service policy at Philips DAP is that nowadays shavers with a Factory Standard Price (FSP) below € 18, - are no longer repaired but replaced. Furthermore, to gain new market share sales promotions are held to attract new customers (users of competing brands, wet shavers). An example of such an action is based on the 'no cure no pay' principle, consumers have the possibility to use the shaver for a specific period on trial before they have to decide if they are prepared to pay for it or not.

This changing role of the customer makes drives the company to a clear shift from product-reliability to a broader definition of reliability that includes the service and function that is expected by each individual customer [Luy02], [Pet03].

### 2.1.3 Globalisation and Segmentation

Increased international competition requires many product development activities to be managed and governed globally, which is very different from purely domestic endeavours. It implies that people in different parts of the world, with different backgrounds and cultural traditions work on the same project. It requires transferring information over big distances and reduces the quality of the information exchanges. The informal network usually prevents problems and is now missing. Another tendency is that companies focus more and more on their core competences. Subcontracting takes place as a result of the make-or-buy decisions that are being made. This results in more parties involved in creating one and the same product, which leads to the same issues as with globalisation [Luy02], [Pet03].

Within Philips DAP this tendency chiefly comes to the surface in the contact and communication with the plant in Zhuhai, China. This communication naturally consists of all kinds of information. For the DQD this means for example synchronising test methods and equipment to be able to compare outcomes, but also gathering information from countries all around the world on market performance of the different shavers. Furthermore Philips DAP attempts to limit its number of suppliers for the parts of the shaver that are purchased. This has as the major drawback that Philips DAP becomes fairly dependent on these suppliers and the quality and reliability of the parts they provide.

### 2.1.4 Increasing pressure on time-to-market

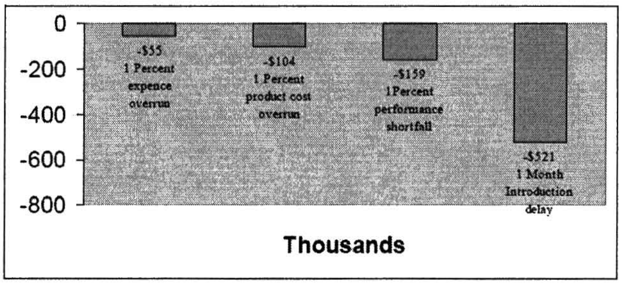



***Figure 2.1 The influence of decision rules on profitability [Smi98]***

Because of the maturity of the market and the presence of strong competitors it becomes more and more important to be the first with new products. Lu Yuan [Luy00] even states 'it is better to be the first to market with a good product than to be last to market with the best product', this also can be concluded from figure 2.1. Time-to-market has a great influence on product development for high-volume consumer products and electric shavers fall in this category of products. When a producer puts his product on the market, the aim is to minimize the time-to-profit. Time-to-profit can be defined as the time between the start of the development of a new product and the time at which the initial investments are recovered. As mentioned before, the producer that comes on the market first with a good product has the shortest time-to-profit, therefore there is increasing pressure on time-to-market [Luy02], [Pet03]. To consolidate its market leadership and stay competitive, Philips DAP recently reduced the length of a standard PCP for shavers from 3 to 2 years.

### 2.1.5 Effect of Trends on Business Drivers

As a result of the above-mentioned trends manufacturers of high-volume consumer products are under pressure because there is a conflict between their four most important business drivers [San00]. These business drivers are:

- ***Functionality:*** is the product able to fulfil its intended function.
- ***Time:*** does the product reach the market at the required moment.
- ***Profitability:*** is the difference between product cost and product sales price adequate.
- ***Quality/Reliability:*** does the product fulfil customer requirements at 'all' customers, not only at the moment of purchasing but also during operational life of the product.

Currently, customers expect ever-increasing functionality in new generations of products. Product quality and reliability is taken for granted: having it is not a strength, but not having it is a fatal weakness [San00]. Connected with this is the change in warranty discussed in section 2.1.2. Without an excellent knowledge about the quality of the products, warranty claims might be much higher than expected [San00]. The high innovation speed has as a consequence that, from sales perspective, products are obsolete in a relatively short period of time. This automatically enforces a sharp reduction in development time and leads to a strong price erosion [San00]. The result is that, if a product is relatively late on the market compared with competitors, it is hardly possible to make profit on it. It can be concluded that manufacturers of high-volume consumer products are confronted with the following situation [San00]:

- The high innovation speed puts pressure on the time to market.
- Customers require excellent product quality and reliability.

The product creation process, from product idea up to and including after sales service, must cope with these requirements. It must be able to identify problems and risks before they happen [San00]. Risks for a design that find their roots in a development process therefore can be divided into two types, technical risks and market risks [Smi91]. The technical risk is the probability of failing to meet the technical targets, e.g. performance, reliability or producibility targets. The market risk is the probability of not meeting the needs of the market in terms of time-to-market, costs or features. These two types of risks interact to increase each other. When technical risks arise in the design this can delay the schedule and increase the time-to-market. At the same time the opposite could be happening, due to a very rigid development schedule there is insufficient time to control the technical risks resulting in higher technical risks (Figure 2.2). This conflicting situation makes demands on different parts of the business process to control these risks; this will be discussed in the following paragraphs.

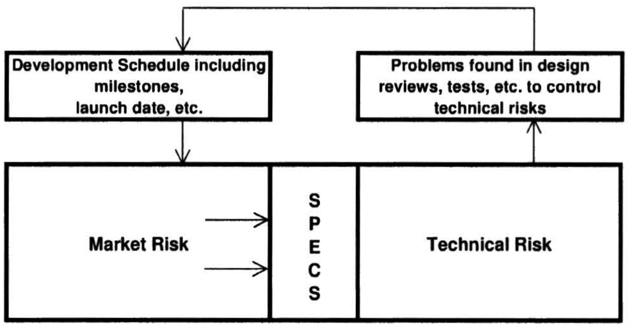



***Figure 2.2 Interaction between technical and market risks [The95]***

## 2.2 Effects on the Business structure

As mentioned in earlier paragraphs there is considerable time pressure on the product development process. For this reason many companies are looking for methods and techniques to accelerate this process. The product development process (PDP) or product creation process (PCP) will be defined in this paper as [Bro00]:

*"A set of transformations via which customer wishes are translated to an operational product (or service)"*

Based on the degree of technical changes in products as well as their applications, two major types of PCPs can be distinguished [Whe92]:

- **Radical PCPs**: These PCPs develop radical products. Radical products are new products, which generally contain new technologies and significantly change behaviours and consumption patterns in the marketplace [Luy02]. At Philips DAP in particular the high-end 'washable' and 'additive' shavers belong to this type.

- **Derivative PCPs**: These PCPs develop derivative products. They use proven technologies to create products based on mature building blocks from existing products. They modify, refine, or improve some product features without affecting the basic product architecture or platform [Luy02]. At Philips DAP especially the down-graded low- and medium-end shavers applying proven components, building blocks and constructions, come under this type.

In order to compete effectively in the marketplace, Minderhoud [Min99] identifies the following requirements for the PCP to be successful:

- Increasing competitive intensity (more new products)
- Increasing technological intensity (frequency of generations and technical complexity)
- Market globalisation (more variants per product)
- Shorter life cycles

Summarized companies are demanded to develop many different products much faster than they used to. To satisfy these new requirements there has been a shift from a functionally structured PCP to a PCP structured according to the principles of concurrent engineering. Both structures and the shift will be described in more detail in the following sections.

### 2.2.1 Functional PCPs

The classical way to structure the PCP is the so-called 'functional development process' (Figure 2.3). In such a process the development of a product is split in a number of different tasks and transformations that are considered to be independent. These activities are operated sequentially according to well-defined procedures and guidelines. Milestones are used to decide whether the process can proceed to the next phase and thus separate the activities of different functionality. When something goes wrong during a certain phase the milestone to the next phase is not passed and all efforts are concentrated on solving the problem.

The advantage of this sequential process is that people concentrate on one aspect during one phase. For example, when a new technology is introduced in the production process, this new technology is analysed in the (pre-) production phase and decisions whether or not to apply this technology are also taken in this phase. Due to this structure there is usually little distance, time-wise, geographical and with respect to the people involved, between a decision and the consequences of this decision. Therefore it is quite common that people whose decision caused a problem are also involved in solving the problem, only a short time later. This way learning cycles with respect to quality and reliability will be comparatively short and efficient.

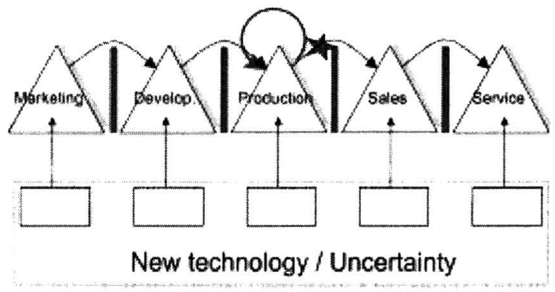



***Figure 2.3 The functional PCP [Ber00]***

As mentioned in subparagraph 2.1.4 there is considerable time pressure on the PCP of high volume consumer products. For many companies the solution for this problem is not to reconsider the basic structure of the PCP but to try to improve the time-performance of the existing functional structure [Bro00]. Lu [Luy00] discusses three classical strategies to achieve a shorter time-to-market. One approach is the attempt to shorten the existing development process. Initially this may lead to short-term successes due to strong motivation of the people involved, but in the long run these time-squeezed PCPs can suffer from a lot of problems and therefore delay in the back-end of the process [Luy00]. Another strategy, often applied by companies driven strongly by quality standards like ISO 9000, is to stick rigidly to procedures. This prevents problems in the back-end of the process, but it will lead to a lack of flexibility and a lack of capability to introduce a new technology [San99]. The third approach implies the use of sophisticated tools in the design process such as QFD and FMEA. According to Lu et al [Luy00] these tools have to be fully embedded in the PCP, in terms of adequate input data and closed feedback loops, otherwise their added value is questionable.

The above-mentioned strategies on time-to-market improvement are all based on the functional PCP. However this structure has some important drawbacks that limit the possibility to shorten time-to-market [Bro00]. First, the major problem of a functional PCP is the fact that it assumes independency of the individual functions. According to Brombacher [Bro00] however, there is ample literature available that decisions in the early phases of the PCP can seriously affect the performance of the later phases of the process. The second loss is the assumed time-independency of decisions, which is disproved by referring to an article in 'Business Week' [Bus90] (Figure 2.4). Changes performed in later phases require far more time and money than changes performed during early phases. Another risk is sub-optimisation, each separate department has its own goal and although the overall goal of the company might be formulated in the mission statement it is invisible in the daily operations [San99]. To deal with the previous conditions a different structure has been developed: Concurrent Engineering.

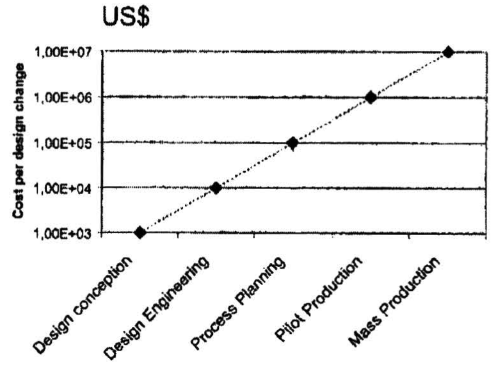



***Figure 2.4 Efficiency of design changes as a function of time in the PCP [Bus90]***

### 2.2.2 Concurrent Engineering

Since approximately 1980 concurrent processes in the field of engineering have received much attention. The idea behind concurrent processes is that downstream activities start as early as possible, even when upstream activities have not yet been completed. In this thesis the concurrent engineering principle will be defined as [Bro00]:

***"A systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule and user requirements"***

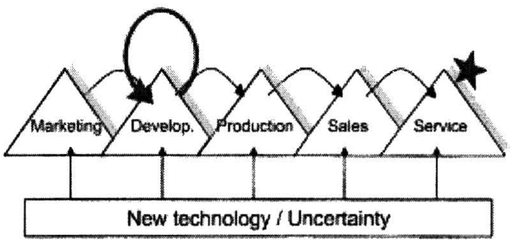



***Figure 2.5 A concurrent development process [Ber00]***

This definition implies that design changes and product optimisation, no matter whether the change involves the design, the production process or the customer use of the product, should be taken in the early phases of the PCP [Bro00]. Although this structure benefits from the far higher efficiency of upstream activities, it puts strong demands on the predictive capabilities within a business process. In a classical, functional PCP problems just occur and need to be resolved otherwise the next milestone will not be passed. In a concurrent PCP problems need to be resolved in the early phases of the development process, long before they actually happen. Therefore, next to finding and solving known problems, a concurrent PCP must be able to predict and prevent all potential problems. The shift from a functional to a concurrent approach has a large impact on the reliability control loops present in a PCP to control the development process; this will be discussed next.

## 2.3 Quality and Reliability Control

In order to control the uncertainties and requirements regarding product quality and reliability during the design process, it will be necessary to define what quality and reliability exactly mean for a product. A common used definition of quality is [Lew96]:

***"The totality of features and characteristics of a product or service that bear on its ability to satisfy given needs"***

The same author defines reliability as [Lew96]:

***"The probability that a product will purpose its intended function for a specific period of time under a given set of conditions"***

Both definitions are very similar; product reliability can be seen as product quality over time. For high-volume consumer products the main difficulty, however, lies in the statement *intended purpose*. For a customer this may mean something different than for a manufacturer of a product and, due to the increasing innovation speed and the great diversity in customers it will hardly ever be possible to give a perfect specification in order to comply with intended purpose.

### 2.3.1 Reliability Control Loops

There are two principal ways of controlling a process, using a feedback cycle or a feedforward cycle [Ber00]. In a feedback cycle, the **output** of a process is measured and compared to a standard by a comparative organ. In case of deviations the appropriate action can be taken through adapting the previous process or adjusting the process parameters. In a feedforward cycle, the **input** is measured and compared to a standard by the comparative organ. Then if necessary the subsequent process or its parameters can be adjusted. To illustrate the operation of both control loops an example will be given using the development process as the process to be controlled.

In the feedback cycle (Figure 2.6), the product that is released for production (the output) is evaluated in production on producibility and accordance to specification. After that, the product is evaluated in the market by the customers on their requirements and demands. Production and customers are the comparative organ. If a design does not fulfil the standards set by production or the customer, the design has to be improved. The development department, which is responsible for the design process, has to make some corrective actions resulting in design changes.

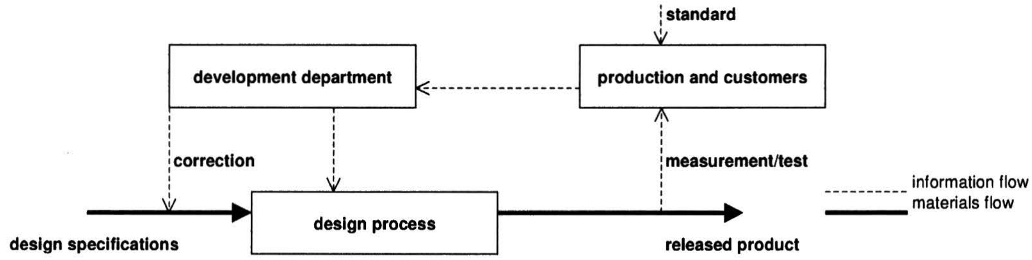



***Figure 2.6 Feedback cycle for a design process***

In a feedforward cycle (Figure 2.7), the characteristics of the design that is not yet finished (the input) are measured by a comparative organ, which in this case is for instance a development quality department. The results of this evaluation are compared to standards that are set for the design. Standards can concern quality, costs, producibility etc. Based on the results of the assessment changes in the design or the design specifications can be necessary. The development department then takes corrective actions before the design process is finished. Feedforward cycles are aimed at finding design problems before the design is released, so that fewer problems occur during production or customer use.

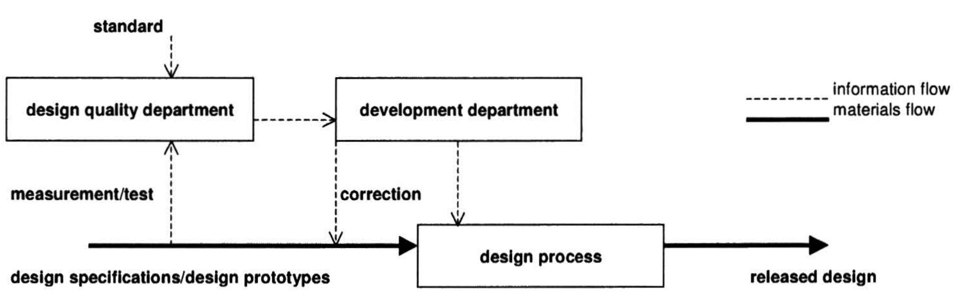



***Figure 2.7 Feedforward cycle for a design process***

In the PCP there is a strong preference for feedforward control loops. This is because the costs of design changes after design release are very high (Figure 2.4) and the customer satisfaction is negatively influenced if waited till problems come up in the field. If a feedforward cycle is to be used, the design has to be evaluated during the process. In the design evaluation all existing and possible problem areas have to be made visible. To be able to evaluate it is necessary to know exactly what the causes of product failure in production and in the market can be. To know potential causes of product failure a properly organized field feedback cycle is indispensable. The demands for this feedback cycle are studied in the following section.

## 2.4 Effects on Reliability Control by Field Feedback Information

A long time ago the development process was simple and the interaction between the client and the manufacturer was very intense in those days. Since the introduction of mass production, the interaction between the client and the manufacturer has become rather indirect. For mass products normally the only contact takes place when the client has a problem with the product and contacts a service centre (SC) [Pet99].

As seen in the previous paragraph Berden et al. [Ber00] describe a feedback loop as: using the output from the subsequent process to adapt the previous process or to adjust this process' parameters. In the case of field feedback, the 'previous process' is the PCP and the 'subsequent process' is the consumer process that the product experiences at the customer. Data about problems that arise in the field should be fed back into the business process and can then be corrected in such a way the specific problems can be stopped from reoccurring in future generations of the product. This way the feedback loop is closed and a learning cycle can be formed.

In spite of the foregoing, SCs are hardly ever seen as essential elements of the ongoing improvement process and are therefore not assessed according to their contribution to the solution of reliability problems. Often the only communication between the SC, the concerned sales organisation and the responsible product division is about money; warranty costs, costs of recalls and liability costs. The only information exchange between designers and SCs usually concerns the serviceability of products [Pet99]. Nevertheless, in order to improve product quality/reliability, the use of field information is essential. If the PCP is observed, this information can be extremely useful in different phases of the development process [Pet99]:

- Before a decision about a new product, family or generation is taken information on the market position and field behaviour of products in these areas is necessary.
- The functional specifications must be realistic, to check this field information related to previous designs must be available.
- If there is no detailed information on the costs of unreliability, it is impossible to estimate financial profit and make decisions.
- A new design is usually to a large extent equal to a previous design. This means that the old field problems are automatically copied into new designs unless there is detailed knowledge on the technical problems of the former product.
- The prototype is subjected to tests. The test program must be realistic; this means that the stresses a product is exposed to must be known, customer use inclusive. Service has insight into these stresses.
- Information about problems that might arise in production becomes partly visible in the field.
- Via trial runs it must be checked whether the field problems as collected by service have been effectively anticipated.

Depending on the goal, different kinds of information in the flow from the field to Philips DAP are relevant. Therefore the information is split in engineering information and statistical information [Pet03].

*Engineering* (technical) information is most urgent, because it is used for finding root causes of field problems. Therefore engineering information should be collected from the very moment that the first customer has a problem with his/her product. This information should at least be available at such a moment that it is possible to prevent the same problem to occur in the next generation of products.

*Statistical* information comes in later and is necessary for several reasons: to determine the absolute level of defects, to find out whether there are modules/components that fail relatively often, to asses the lifetime distribution of the time to first failure, which is, for example, relevant for warranty purposes and to determine whether the company is learning from the past.

Petkova [Pet03] distinguishes a number of problems that may occur regarding the collection of field feedback information:

- Information comes in late;
- The available information is not complete enough for quality improvement;
- Information is not fed back to the right place in the PCP;
- Information is often hidden in a huge amount of data that is difficult to analyse.

An organisation can only have the right data available at the right places, when it organises the collection of useful data, analyses these data and distributes the right information to the right people. Many classes of data can be distinguished; this report will concentrate on reliability oriented failure data, which is data from testing, from production and from the field. In order to be able to react to and learn from undesirable deviations from the process (PCP) output a four-step procedure is necessary [San00]:

- ***Measure.*** If the process output strongly deviates but is not measured, it is unlikely that any corrective action will take place.
- ***Communicate.*** In order for a process to react, certain relevant activities in the information flow leading to the process output will have to be adapted. This requires at least that the corresponding actors are informed.
- ***Analyse and control.*** Only when root-causes of deviations are known corrective actions can be implemented effectively.
- ***Adapt.*** Parts of the process or process structure have to be adapted to prevent that problems repeat themselves.

For companies it is a challenge to organise the business processes in such a way that these four steps are really executed. To analyse the response of a business process on disturbances in order to be able to improve the business process, the Maturity Index on Reliability (MIR) was developed. The MIR measures the quality of the response on a five step scale (0-4) where steps one to four relate to the four levels of response mentioned above. This is schematically reflected in figure 2.8 below.

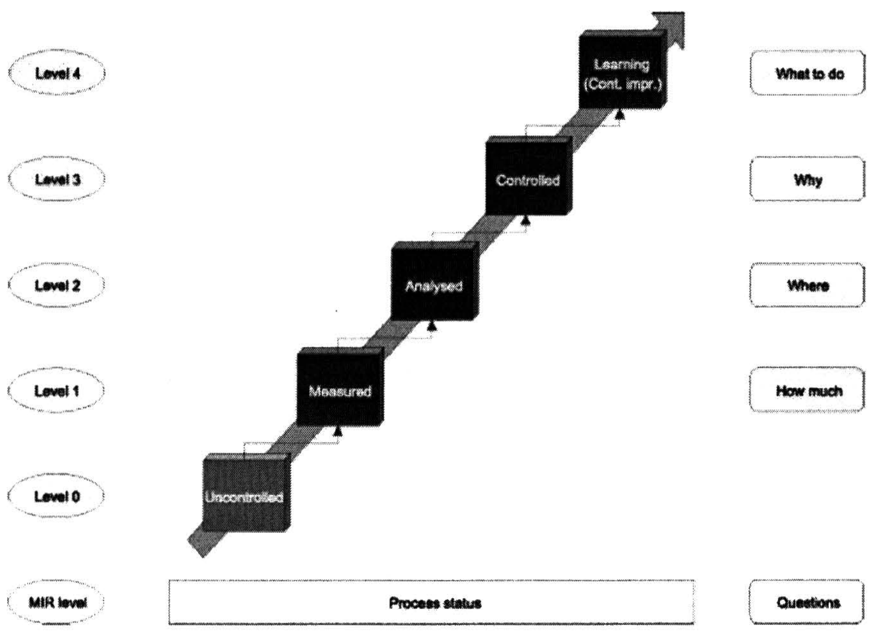



***Figure 2.8 The MIR model [San99]***

This results in the following five levels of capability to analyse and control problems [San00]:

- ***Level 0 – No information available***
  The manufacturer has no relevant quantitative evidence of the field behaviour of the products. Consequently, there are no control loops from Service back to Production and Development.
- ***Level 1 – How many problems?***
  The manufacturer has quantitative evidence of the process output in terms of fall-off and field failures and the information is fed-back into the process, but the origin of the problems is unknown.
- ***Level 2 – Where do they originate?***
  The manufacturer has quantitative evidence of the field behaviour of products, knows the origin of the problems, has the corresponding control loops, but does not know what actually causes the problems.

- ***Level 3 – What is the root cause?***
  The manufacturer has quantitative evidence of the field behaviour of its products, knows the origin of the problems and knows what actually causes them, has the corresponding control loops and is able to solve the problems. The manufacturer is, however, not able to prevent similar events from happening in the future again.
- ***Level 4 – What can be done to prevent reoccurrence?***
  The manufacturer has quantitative evidence of the field behaviour of its products, knows the origin of the problems, knows what actually causes them and what to do about it. The level of knowledge is such that the manufacturer not only knows root causes of problems (technical and organisational) but is also able to anticipate and prevent similar problems in the future. All corresponding control loops are in function.

## 2.5 Effects on Reliability Testing

In the previous paragraphs the effect of the present market trends on the PCP were discussed. These trends make the classical functional PCP shift to a concurrent engineering development process. As a consequence, predicting and preventing unknown problems has become equally important as finding and solving known problems. To achieve this, next to properly organised feedback control loops there is a strong preference for feedforward control cycles, this change has a major impact on the role of testing in the development process.

As seen in the previous paragraph, milestones separate the different phases in a functional PCP. These milestones are only passed if certain conditions are fulfilled e.g. the accompanying tests have a positive result. A classical test satisfies, when a product prototype comes available, the ability of the product to meet its specifications. In a classical sequential, development process functional aspects are validated in the design phase, aspects of production are validated in the (pre-) production phase and aspects of customer use are validated at the moment when a larger quantity of products becomes available for the first time. This causes, however, a direct conflict with the concurrent engineering development process because in such a process potential problems, found normally during product tests, should have been identified already during the earlier phases of product development [Luy00].

This can be diagrammatically clarified by the so-called V-model described by Forsberg and Mooz [For96]. This model describes 'the technical aspect of the project cycle'. The model (Figure 2.9) starts with user needs on the upper left and ends with a user-validated system on the upper right. On the left side, decomposition and definition activities resolve the system architecture, creating details of the design. Integration and verification flows up and to the right as successively higher levels of subsystems are verified, culminating at the system level. Verification and validation progress from the component level to the validation of the operational system. At each level of testing, the originating specifications and requirements documents are consulted to ensure that components / subsystems / system meet all specifications.

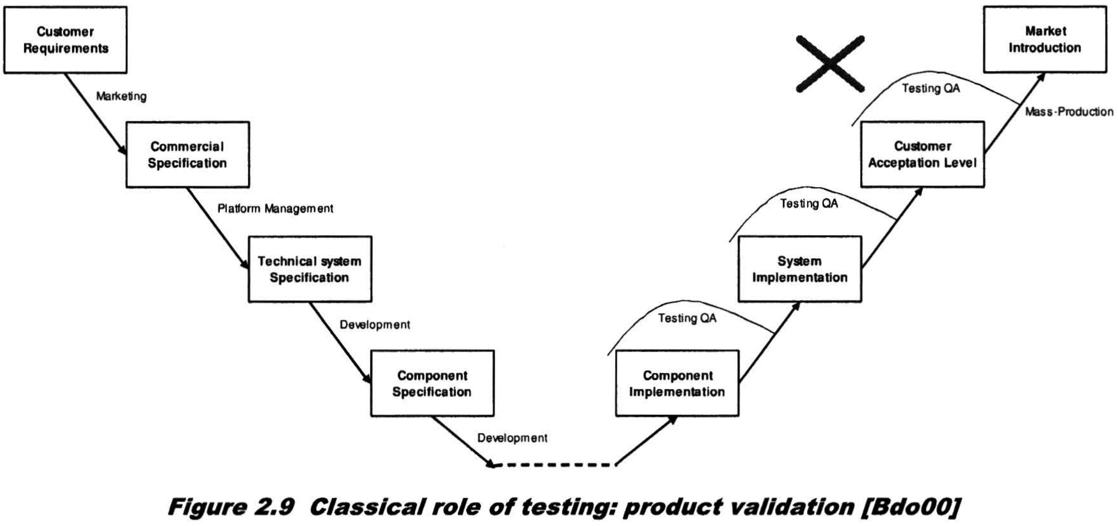



***Figure 2.9 Classical role of testing: product validation [Bdo00]***

This way of working only is effective when no uncertainties do exist. This is the case in a derivative PCP where products are created based on mature building blocks from existing products, with known production techniques for a known market with familiar use(r)-characteristics. In this case it is possible to write a complete set of technical specifications that can form the limits of a control chart to control design quality and reliability. Yet when a product is developed containing new technologies, new functionalities or for an unfamiliar market segment with unknown use(r)-characteristics, there do exist uncertainties that can lead to quality and reliability risks and merely validation tests do not longer satisfy.

The disadvantage of a validation test is that it is always reactive and never proactive. A test pass provides no information on the conditions under which failure occurs. And if a serious product reliability issue does arise from the test, it can be too expensive and too late to introduce the necessary design changes. In the highly competitive market today where many new technologies are employed and where customers expect reliable products at a competitive price, there are many risks that the PCP has to take into account. As a result of the complexity of current products and the great diversity in use(rs) of a high-volume consumer products it is nearly impossible to write a 100% watertight specification, besides the customer also will complain when the product fails outside of these specs. This leads to the conclusion that in case of innovative products where lots of uncertainties are involved, validation tests no longer are suitable to assist the PCP to tackle all these risks. Therefore there is a strong need to supplement validation tests by something giving more information earlier in the PCP [Luy00].

In a concurrent engineering process it is therefore possible to identify two classes of tests: *analysis* and *validation* tests. An analysis test is a test where potential critical aspects of a product are tested early in product development. The test is 'failure oriented' and aimed at confirming or rejecting risks that may or may not happen in a future product. Testing the product at the earliest possible stage in the PCP is desirable because design improvements are least costly and time-consuming when the design is still not definitively defined and fewer agreements with third parties have been settled. An analysis test is recommended under this condition to be performed at the very early stage of the PCP where a product prototype with limited final product information can be made available. It is meant to invoke realistic product failures early in the PCP and to detect as many failures as possible. Then control loops and follow-up actions should be taken to prevent and control those potential failure mechanisms and optimise the design. So an obvious challenge is how to do such analysis tests [Luy00].

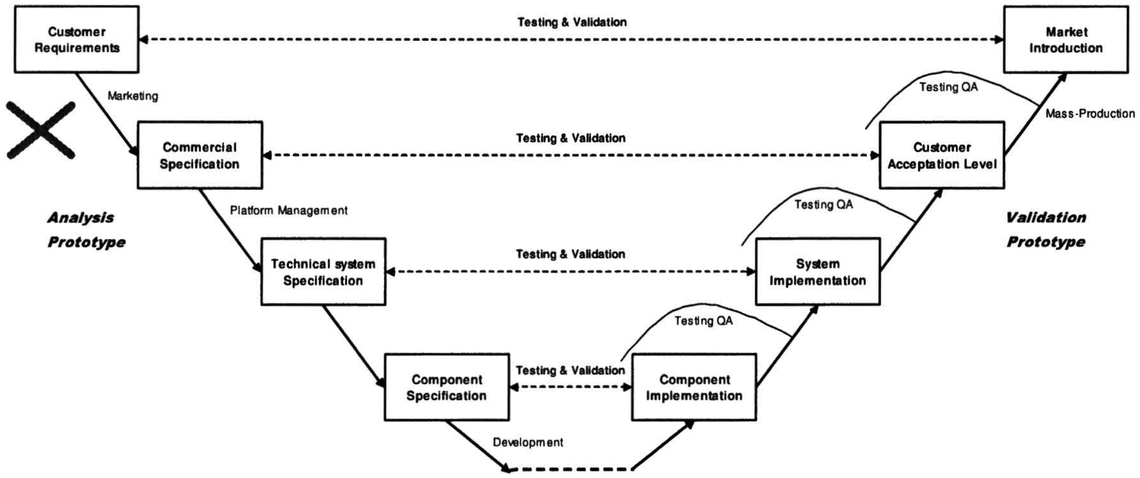



***Figure 2.10 Required role of testing: early product optimisation [Bdo00]***

In summary it can be stated that in a time-driven PCP there is a need for an analysis test that is fast and cost effective. Besides finding and solving known problems, the goal should be to predict and prevent all potential problems. It is essential to secure the knowledge building and exchange within the development process and to have a fast field feedback flow as described in the previous section.

# 3 Problem Description

Now, with the context of this research being outlined in the previous chapter, this chapter will deal with the actual situation at Philips DAP and how quality and reliability is controlled during the PCP. In order to allow a better translation of product reliability to the underlying business process, first a failure classification system will be introduced.

## 3.1 Reliability problems for shavers

Demands on product quality and reliability do put the greatest strain on the concurrent engineering process. This is a consequence of the maximum time distance between decision and validation of the decision, as reliability problems will be mainly observed at the customer, during or after the final phases of product development. In a modern time-driven PCP, risks with respect to quality and reliability have to be addressed very early in the development process. As in those early phases actual field information often is not available, predictive models will have to be used to allow early estimation of reliability [Bro00].

The use of predictive models for reliability analysis is not new. Already since halfway the last century (military) industry has been paying attention to this topic. The approach was mainly focussed on components, which at the time formed the dominant category of field failures. The behaviour of those components was described on the basis of the well-known bathtub curve (figure 3.1).

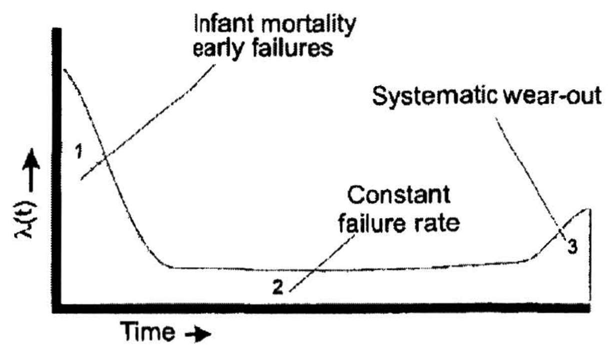



***Figure 3.1 Bathtub curve***

The three phases of this model can be characterized by the following properties:

- **Phase 1:** The "infant mortality period", with an increased failure rate as a result of design- or production flaws.
- **Phase 2:** The "random failure" phase is the phase for normal use of adult products with a constant failure rate.
- **Phase 3:**Increasing failure rate that is attributed to end-of-life degradation and wear-out

To deal with the first and third phase an elimination strategy could be used. The products were thoroughly tested to eliminate weaker products. And new products replaced products in the third phase. So only products within phase 2 remained. In this phase the failure rate is constant and therefore easily predictable. However, nowadays the applicability of the constant failure rate model is limited by a number of reasons. For high-volume consumer products reliability is not only determined by the reliability of the separate components but product reliability should be modelled as a function of components, the way the products are designed and manufactured, and the way customers and end-users use these products. Another reason is that in time-driven PCPs there is no time available either to test individual products until they have passed the phase of infant mortality or to apply a rigorous test program that will ensure mature designs, both on component and product level [Bro00].

Therefore a roller coaster failure rate curve has been developed [Won88], to replace the constant failure rate to model the product behaviour generally in the field (figure 3.2). The roller coaster failure rate curve uses four instead of three phases and concentrates strongly on the behaviour of (weak, extreme) sub-populations within a large batch of products [Luy00]. The different phases can be described as follows [Luy00], [Bro00]:

- ***Phase 1 - Hidden 0-hour failures***

Sub-populations of products already defective at t=0. Reasons for failures at t=0 can be products outside specification that reach the customer or products inside the suppliers specification but unacceptable to the customer either due to an incomplete specification or a different perception of the product by the customer.

- ***Phase 2 – Early wear-out failures***

For high-volume consumer products it is not unlikely that there are considerable differences between either any two items of a product or between how any two customers use the same product. This leads to a situation where such a sub-population of products will be reported defective far earlier than the main population.

- ***Phase 3 – Random failures***

Products are designed to be used against anticipated ('normal') user conditions. It is, however difficult to anticipate and to design against all events to which a product can be subjected. The failures in this phase are defects, caused by random events, either internally in the product or externally from customer use or other external influences with a strong 'random' character.

- ***Phase 4 – Systematic wear-out***

Many products show some form of degradation over time. Well-known time effects are corrosion of metals and increased brittleness of plastics. Although the level of degradation will be different for every product, there will be a moment in time where these failures start to dominate the failure rate curve and lead to an increasing failure rate.

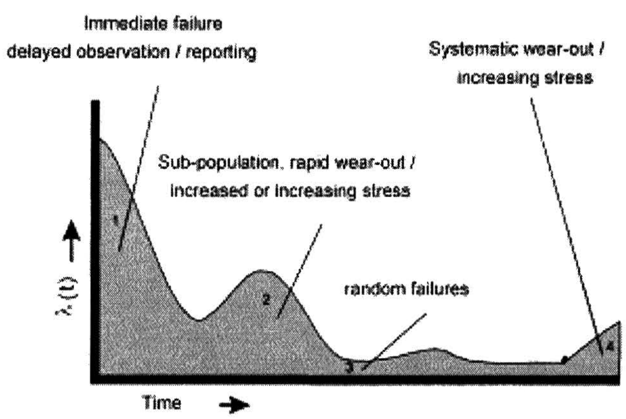



***Figure 3.2 Roller coaster failure rate curve [Luy00]***

Which class of reliability problems is relevant for a product is strongly dependent on its lifecycle strategy; depending on developments in technology, the market, and the type of product that is being developed companies will have different focus with respect to product reliability [Bro04]. Although in reality there will be a very large number of different lifecycle strategies, Brombacher et al [Bro04] identified three generalized business processes:

**A.** Business processes depending on products where the economic lifetime[1] is much shorter than the technical lifetime[2]. Examples of products in this category are personal computers and other products with a strong IT content (e.g. mobile phones).

**B.** Business processes depending on products where the economical lifetime is comparable to the technical lifetime. Products like cars or more traditional consumer products that have a modest degree of innovation belong to this category.

**C.** Business processes depending on products where the economical lifetime is much longer than the technical lifetime. For example capital intense systems, like oil refineries, are such products or systems.

[1] Economic lifetime is defined as the average time where it is justified to replace the product for economic reasons.

[2] Technical lifetime is defined as the average time that a product requires to reach end-of-life due to technical failures.

As a result of aforementioned trends on the market of high-volume consumer products, phase 1 and 2 become very relevant. Because of the short market windows, products are introduced on the market before the flaws in phase 1 and 2 are 'tested out'. Particularly for highly innovative products it is unlikely that phase 4 (or even phase 3) will be reached. There is a large chance that by the time the product starts to show such behaviour there are better or newer products on the market that offer more functionality at lower costs [Gra01]. Consequently, reliability prediction will more and more focus on phase 1 and 2 of the 'roller coaster' –curve. To successfully predict the reliability for these phases, it is necessary to obtain detailed knowledge on the interaction to expect between consumer and product during normal and especially extreme use at explicit but also at implicit product specifications. By extreme use at implicit specifications for example unexpected (incidental or intentional) interactions with the environment or with other products in and out of the formal specifications of the manufacturer are meant. In the past problems due to implicit specifications (or even out-of-spec use) were not seen as reliability problems. Since, as mentioned before, the attitude of the customer shifts from product conform to function- or service- related, it would hardly be possible to use formal product specifications as a boundary for product quality. Given the present-day product complexity, it is particularly difficult to write an all-embracing watertight specification. Besides, most users are only partly interested in this. When customers come across serious problems with the product outside of the formal specifications this will be a reason to complain or search for another supplier [Gra01].

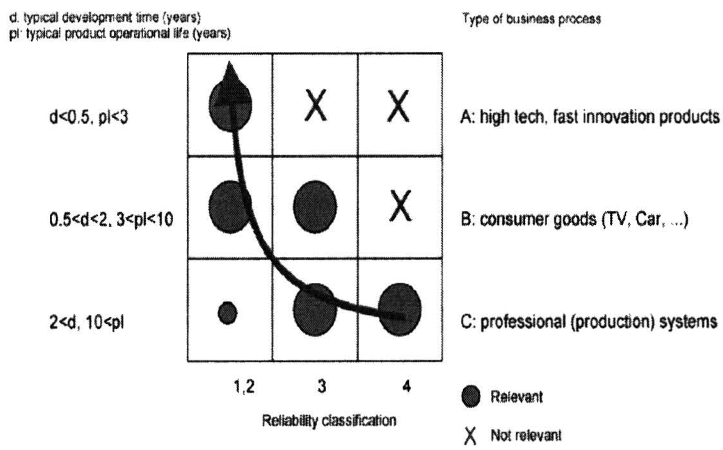



***Figure 3.3 Relevance of different failures for different business processes [Bro04]***

The generalized business processes, the relevance of the different phases of the roller coaster curve and the shift under the influence of business trends are shown schematically in figure 3.3. When the business environment of Philips DAP shaving is observed according to this theory (7 years technical lifetime requirement, 2 years of development time) it can be concluded that it belongs to class B, consumer goods. Therefore reliability control during the PCP should focus on the first three phases of the roller coaster curve.

In the continuation of this chapter first the PCP of Philips DAP will be described including a number of different methods used to control the quality and reliability of the design during the development process. Next is focussed on the two principal activities of the DQD. These will be described and assessed based on the requirements described in this section and in Chapter 2.

## 3.2 The PCP

Philips DAP uses the term 'Product Creation Process' to address the development process. In section 2.2 the product development process was already defined; another similar definition is:

***"The sequence of steps or activities which an enterprise employs to conceive, design and commercialise a product [Epp00]"***

The PCP is described in several documents used within Philips DAP. The product creation process consists of several phases, which are concluded with a milestone, as depicted in figure 3.4. Each of the phases between the various milestones consists of several main events that for their part are built from smaller sub-events.

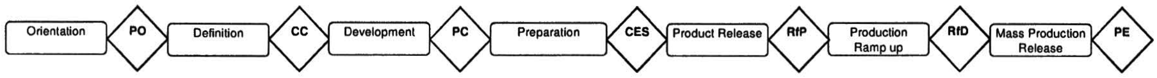



***Figure 3.4 The phases and milestones in the PCP***

To give an impression of the development process of the shaver, the different phases and milestones that are part of this process are described here.

**Orientation phase > Project Order (PO):** The PCP always starts with a project assignment. Based on this project assignment the project team investigates the technical options to fulfil the commercial wish specification. The collection of these technical options is the input for the design direction. After a face value test, feasibility study of the several technical options and financial validation of them, the main concept, both internal (modules) and external (design) will be fixed.

**Definition phase > Concept Consolidation (CC):** After choosing the winning design and technical concept, the design team will work out the details of this concept in terms of feasibility, production structure, supplier choice, planning and capacity to prepare the project contract. The project contract contains all these issues, which will be committed by the Centre of Competence (CoC) in terms of project results (product specification, time and financials) at the end of the project. Next to the preparation of the project contract, the design files are worked out and finished.

**Development > Prototype Consolidation (PC):** In this phase the technical concept is worked out in 2D- and 3D-CAD files and the supplier selection will be finalized based on the offers of non-SMOB (structural make or buy)-parts to prepare the tool-making process. Based on known modules and parts, the production equipment is defined, technically validated and investment budgets are prepared. At the end of this phase a working prototype is available.

**Preparation > Consolidated Engineering Samples (CES):** After consolidation of the prototype, the necessary tools and equipment will be ordered and the main budget has to be approved. After FOT (First-off Tools) samples are assembled manually or by equipment if available. Based on the first product release tests the project team sets up an improvement plan and confirms that the conditions are suitable to pass the product release and production start at the agreed time.

**Product Release > Release for Production (RfP):** During this phase the product is released both visual (Design release) and functional (General Test Specifications Shavers). The products are made on the final production tools and equipment. Based on the pilot production run an action plan is available to release the process and equipment. A ramp up plan agreed by Logistics, Production and Suppliers is in place. 0-hour and lifetime quality of the finished shavers needs to be proved and the shaver is released for production.

**Production Ramp up >Release for Delivery (RfD):** In the Production-Ramp-Up phase the process capability study is finished and the equipment is transferred to production. Then introduction quantities for the market launch are produced. A final check takes place on available stocks and the products are released for delivery.

**Mass Production Release > Project End (PE):** When the RfD-milestone is passed all aspects with relation to mass production have to be validated and then the project team transfers the product to production. Also the first market feedback comes available and is analysed and the repair instructions for the service department are composed. Then the project is evaluated and reaches the final milestone, Project End.

## 3.3 Reliability Control in the PCP

During the development process Philips DAP attempts to control the quality and reliability of its products in various ways among which: design rules, risk analysis, target specification and verification program (TSVP), field feedback information and design/product testing. In this section the first three of these methods/tools will be briefly discussed, then in the next paragraphs a more detailed evaluation of the field feedback control loop and the test program will be given.

### *3.3.1 Design Rules*

The database of so-called design rules (DR) consists of information (rules) that describes how certain design-parameters (of products, processes or means) can be designed first-time-right because they are derived from an already established solution. This way a repetition of product(ion) problems can be prevented, a faster and smoother production start is possible and timely in a development project it is possible to obtain insight on financial and quality consequences of certain choices to be made. In spite of the presence of these design rules a number of failure mechanisms is repeating in successive generations of products. Leading to the conclusion that the use of available documented information is limited. Besides, Design Rules are only effective when the degree of innovation is low.

### *3.3.2 Risk Analysis*

As emphasized in the previous chapter, in time-driven PCP's such as that of Philips DAP reliability should be managed proactively. This implies that potential reliability problems are to be identified and managed far before their occurrences. The PCP of Philips DAP contains therefore a number of reliability prediction methods to manage potential reliability problems. The main method used by Philips DAP for this purpose is the so-called Failure Mode and Effect Analysis (FMEA). It identifies and, where necessary, removes potential failure modes during different phases of product development, resulting in a product-FMEA, means-FMEA and process-FMEA. The main objective is to prevent potential reliability problems from reaching end-users. During an FMEA session the following information was generated:

- Which components/parts or manufacturing process steps does the product require?
- What is/are the function(s) of these components/parts or manufacturing process steps?
- What are the potential problems related to theses components/parts or manufacturing steps?
- What are the causes of these problems?
- What are their effects?
- What are the appropriate measures and who is the responsible person to take this actions?
- When is this action completed?

To be able to rank the risks and monitor the improvement actions in the PCP Philips DAP uses a gravity factor and an evolution factor to indicate respectively the severity of the potential reliability problem and the status of these potential problems. The gravity factors that are used are: S, A, B, C and D. Decreasing from very severe safety problems (S) to a problem that is accepted by management or the customer (D). The evolution factors are 0, 1, 2, 3 and 4. With 4 meaning that the cause of the problem is not known and 0 that a solution is already introduced. This FMEA sheet then is updated at the next milestone. An example of an FMEA worksheet is given in Appendix F. Then the (potential) problems identified in the FMEA are categorised according to their gravity and evolution factors. Then the number of (potential) problems for each category is counted and filled out in a maturity grid as is depicted in Appendix F. In this grid the most severe problems without a known cause are in the upper left corner and accepted problems with an available solution are at the bottom right corner. Then for each of the PCP-milestones a border is indicated above which no problems are allowed.

This seems a useful tool for predicting potential problems, however it has a number of disadvantages. FMEA requires very detailed and thorough information as well as precise customer specifications [Gan05]. Moreover, tools such as FMEA are only useful if the results are actively used in the process and there is a certain degree of verification/validation of the resulting information later [Bro00]. A questionnaire among the users of FMEA at Philips DAP revealed that users think drawing up a FMEA is a tedious process. They also indicate that the process is often too much focussed on solutions. This matches the finding of Ganesh et al [Gan05] that a traditional FMEA focuses on reducing the risk without considering the uncertainty involved in the prediction, work stops when the risk seems to be reduced. Besides, at Philips DAP the FMEA does not form the input for analysis tests that confirm or reject a particular risk.

### 3.3.3 TSVP

The Target Specification & Verification Program (TSVP) is a part of the YES! improvement program (2004). The Goal of the TSVP is to have a proven construction at the 'concept proven' event in the PCP. It is not a toolbox, but a method to come with defined steps from a clear specification to a proven construction to eventually product release.

The TSVP is developed because in practice it sometimes seemed easy and acceptable to start constructing without having a clear view on harmonized targets. However, this results in an endless discussion about results mismatching expectations. Without a target (specification) it is impossible to judge a certain function, which is necessary to proof it. Focus on specifications in the early stage of the development project enables a clear discussion about needed information from the different players in the project and prevents easy specification changes because the impact is more obvious.

The **target specification** consists of three specification documents: commercial specification, functional specification, and technical specification. First the commercial specification is written by the commercial department this gives information about the kind of product that will be sold including market positioning, timing, pricing, etc. This document forms the input for the design process. Derived from this commercial specification a functional specification is drawn. This document describes where and how the shaver is used and stored; it lists functions, judgement criterions and judgement levels in the perspective of the user. The technical specification describes how the shaver shall work and will be tested to fulfil his specified functions in the specified lifetime, concerning for example legal, environmental, service and process related issues.

The **verification program** is presented in the so-called Q-book. This Q-book is used to monitor the current status of evidence for the critical targets defined during target specification. For each milestone in the PCP a defined level of proof is required. In the Q-book is visible which proof is planned or available for each critical parameter. In the early phases of the PCP this proof is purely theoretical, mathematical or based on 3D CAD drawings. Later, when the parts from the final production are available the functions and make ability will be released according to the General Test Specifications Shavers (GTSS).

However, the above method is based on specifications and focuses on 0-hour functionality characteristics. Extreme products, extreme users and a combination of both are left out of consideration. Therefore the method is not able to optimise reliability behaviour in the early phases of the PCP for products that use new components, building blocks or (production) technologies

## 3.4 Field Feedback

When problems with a product occur in the field, Philips wants to know this as soon as possible to take suitable measures. In case of serious safety problems the product has to be called back to avoid more disastrous consequences, in case of less serious problems Philips wants to know them to prevent them in future generations of products to improve customer satisfaction.

### 3.4.1 Structure

In order to get an idea about the speed and quality of the field feedback flow, a logical first step is to map the feedback flow and to identify the possible sources of information. In figure 3.5 the structure of the field feedback flow is presented.

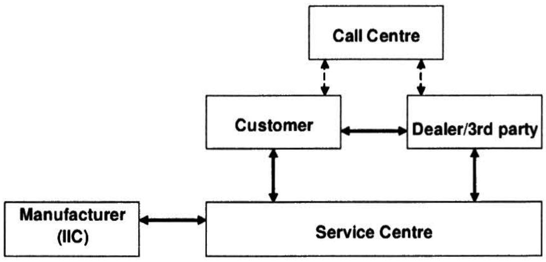



***Figure 3.5 Field feedback flow***

When a customer encounters a problem with his shaver, there are three possible parties to contact:

- **Dealer**

Besides selling the product, the dealer's task is also to handle customer questions. When a customer contacts the dealer there are several options to solve the problem. Either the salesman has enough product knowledge and general experience to answer the questions or to explain to the customer how to use his shaver. Or, if necessary, the dealer can contact a call centre to ask for information. When the dealer establishes that the device needs to be repaired, he will advise the customer to send the product to a Service Centre. In case of difficult questions and serious problems such as missing parts or shavers that are dead on arrival, the dealer can turn to the National Sales Organisation (NSO) in his/her country and the NSO will support and supply the dealer. The contacts between customer and dealer are not registered and no feedback to Philips DAP exists.

- **Call Centre (CC)**

When the product knowledge of the dealer is inadequate he can choose to forward the customer to a Call Centre (CC). Here a lot of experience in dealing with customer complaints is present in a continuous growing knowledge base. When a customer call comes in it is either solved this way by a CC employee (soft failures) or the customer is instructed to send his shaver to a Service Centre (SC). In case of new or unknown problems the CC informs the NSO, which in its place forwards this information to the Drachten plant.

- **Service Centre (SC)**

The task of a service centre is to repair failed products. In most of the countries where the Philishave is sold, these SCs are outsourced and therefore only focussed on minimizing costs and not on collecting engineering information for reliability improvement. For that reason only quantitative data about the number of repairs and used modules and components is available. The NSO collects the data from the SCs in the region and communicates this with the Business Unit Shaving. In the Netherlands the situation is different because the SC is located at the manufacturing site in Drachten. This way the information exchange between designers and service centres is stimulated.

The Drachten location also acts as a so-called Initial Investigation Centre (IIC). This implies that when a new type of shaver is launched in a country, the first 500 shavers that show a defect are collected at the local SCs and directly forwarded to the manufacturing plant in Drachten. There these failed products are thoroughly investigated to detect the failure mode and root cause that occurred, and immediate action can be taken.

### 3.4.2 Quality of the Feedback Flow

All repair activities performed by the SC are recorded in job sheets (Appendix E). A job sheet contains the following data:

- Reference number
- Product type
- Serial number
- Date of purchase (if available)
- Date of complaint
- Warranty (Y/N)
- Analysis department
- Complaint
- Repair
- Symptom
- Replaced parts
- Examination of failure

The 'Complaint' is the failure as experienced by the user, under 'repair' is described what the mechanic at the service centre has done to solve the problem and in the form 'Examination of failure' the failure mode is analysed by the SC operator. When anything unusual happens action can be taken and the failure mode can be further analysed by the responsible development department. The information that results from the repair activities at the SC is collected in the so-called CaRIS (Call-Rate Information System) application. The CaRIS tool is directly accessible from the computer desktop for all authorized employees to analyse failure data, e.g. Pareto diagrams of the repairs can be made.

However this is not an objective system as it leaves room for interpretation. There is more than one employee that checks the returned shavers and unless recorded in the service manual there are different ways to repair a defective shaver. Moreover also the codes used to indicate a specific symptom, defect or repair are not applied in a uniform way; i.e. the same failure modes get a different symptom code. If a certain part is replaced it does not automatically mean that the part is not reliable, it can also signify that the replacement of that certain part is a good way to get the shaver working again. The above implies that the quality of the data as collected via the SC in the CaRIS is reduced in such a way that it gets more difficult to be used as engineering information to improve the quality of future generations of shavers.

### 3.4.3 Speed of the Feedback Flow

In order to get an idea about the speed of the information flow, for a particular high-end shaver with a number of new components/building blocks and technologies all problem reports from the first year after production start were investigated. Figure 3.6 shows the number of failed products per week, based on data from CaRIS. Week one is the first week after production start.

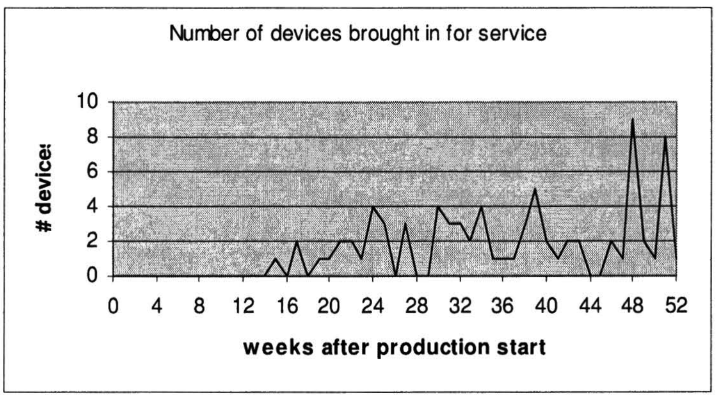



***Figure 3.6 Number of devices brought in for service as a function of time***

As can be seen, the first device was brought in 15 weeks after production start and after this the number of incoming devices increases. From production start it took more than 26 weeks until 20 devices were brought in for service. If first feedback comes in later than six months after production start, it certainly cannot be called *Fast* Field Feedback. Therefore it is interesting to examine how long it takes until customers start reporting problems to the Dutch service centre. In order to give a complete picture about the throughput time of at least one product, it was analysed what the average time is between production date and problem report date for the same type of products as the one used in figure 3.6. From 600 problem reports the time between production date (gained from the serial number) and purchasing date (gained from the receipt, when available) was calculated. The result is presented in figure 3.7.

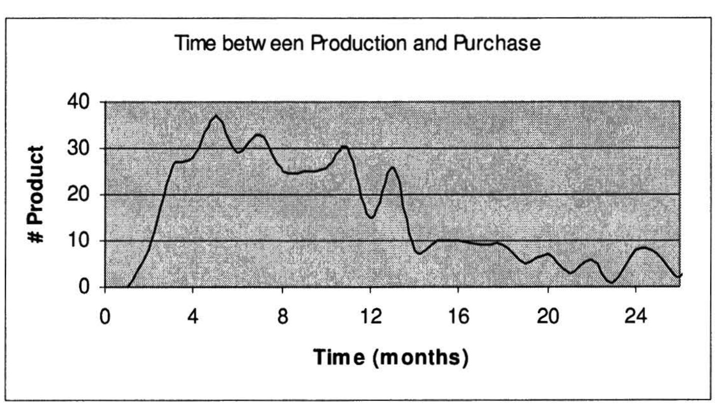



***Figure 3.7 Time between production and purchase***

From the data used to draw figure 3.7 it can be calculated that only 40% of all products are sold to the end users within six months after the shaver was produced. These figures suggest a long delay between production start and customer complaints, therefore the time between purchasing date and problem report date was examined for the same 600 products. The result can be seen in figure 3.8.

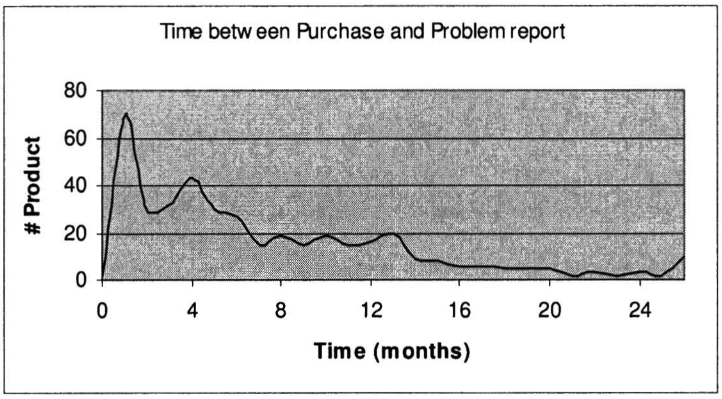



***Figure 3.8 Time between purchase and problem report***

From figure 3.8 it can be derived that from the shavers that fail and are offered for repair to the SC, 57% fails within its first six months after purchase. This could suggest a substantial share of phase 1, hidden 0-hour, and phase 2, early wear-out failures. But because the sales data was not included in this graph and the product is still on market it does not prove this relation and needs further research.

To get an idea of the character of these failures the field feedback information of the shaver type also used for the determination of the speed of the feedback loop in this section, was looked at in more detail. From this observation it can be concluded that almost all problems with shavers that are repaired at the SC fall in the first three classes of the roller coaster curve. An exception is the wear-out of the shaving heads; obviously these are subjected to mechanical wear due to the constant rotation and cutting of thousands of beard hairs. Therefore these shaving heads are not included in the warranty conditions. For an optimal shave, customers are advised to replace the shaving heads at least every 2 years. However customers dissatisfied with the shaving performance still return the shaver to a SC and contribute to the FCR and service costs.

### 3.4.4 Product Performance Measurement

After the shaver is released into the market, Philips DAP wants to know the actual field reliability of the product to validate the prediction and to describe the performance of the business process. The metric used to quantitatively express the field reliability is the Field Call Rate (FCR). The FCR is a standard metric used throughout the entire company of Philips NV. The actual calculation is more extensive but in short it can be summarized as the ratio between the Moving Annual Total (MAT) of calls and the MAT of products inside of the warranty period expressed in per cents:

$$FCR = \frac{MATcalls}{MATproductsInWarranty} * 100\%$$

The data that is used to calculate the FCR consist out of hard reliability failures and out of so-called nuisance calls (No Fault Found) because they are gathered at the Service Centres. The FCR expresses what fraction of the products fails during the warranty period. But due the use of moving annual averages the metric has a weakened and delayed reaction to abrupt changes in sales or repairs. Moreover, the expression does not take into account the age of the product on the moment of failure. Besides, in the calculation used to determine the FCR, Philips DAP assumes that the time between delivery to a NSO and sale to the end-user is 2 months; figure 3.7 indicates that this delay is significantly longer. Therefore the FCR can only be used as a comparative performance indicator and is useless for close monitoring of the field behaviour of new products. For this purpose a number of other metrics, like estimators for the hazard function, are presented in literature [Pet00] that make full use of the available data.

A remarkable fact when the FCR is considered is that the FCR numbers of many high-end washable and additive shavers with new technologies or developed for a relatively unfamiliar market are up to three times as high as the FCR numbers of medium- and low-end shavers that make use of proven building blocks.

### 3.4.5 Conclusion

In summary it can be said that Philips DAP has a substantial strength having a Service Centre in-house. This provides the opportunity to collect useful information about failures arising at the customer. In case of new or unknown errors the responsible development department can investigate the failed products to identify failure modes and root causes and take adequate measures to prevent re-occurrence of the failure. However, these opportunities are not always completely utilised. Sometimes it is obvious what the origin (such as design, production, material, etc.) of the problems is. However, when this is not obvious it occurs that a certain problem is not dealt with because none of the departments takes the responsibility for it. When the origin of the problem is known the failure is investigated by the responsible department to find the root cause of the problem and to solve it. Yet, in a number of cases a solution for the problem is designed before the exact root cause of failure is known. This can lead to a solution that is not completely adequate or optimal and in addition the same problem also can arise in later generations of shavers. To become a learning organisation it is important that all available feedback information is used to determine the technical and organisational root-cause of the failure and to identify subpopulations of extreme products and/or users. Then this information should be fed back to the right place in the organisation so adequate measures can be taken to prevent re-occurrence of the failures.

Another weakness of the field feedback cycle at Philips DAP is the delay present in the supply-chain between production and failure report in combination with the metric used to quantitatively express product performance in the field. The delay is principally caused by the time between production of the shaver and the moment it is purchased by the customer. In 60% of the examined cases this delay is more than 6 months. Slowing down the field feedback cycle means it becomes impossible to react quickly on unknown field failures and make the necessary design or process changes. Moreover it takes a very long time before the success of a certain design change can be observed. In addition the metric used to express the performance of the shaver in the market, the FCR, is a very slow metric due to the use of moving annual averages and does not make full use of all available data (e.g. date of sales) and is therefore fundamentally incompatible as a figure of merit for class 1 and 2 failures [Bro04].

Customers will always find reliability problems, however it is better (cheaper, faster, better for reputation) to find all product flaws and weaknesses before the product is released. In the next section it will be determined if the test program of Philips DAP is capable of finding all product flaws and weaknesses and stimulate product optimisation.

## 3.5 Reliability Testing

Field information is the most direct information source. Tests have to tell something about product behaviour in the field and about the interaction between product, user and environment. Philips DAP wants to know all the product weaknesses and possible causes of failure, so that it can improve the product and its reliability before market release. In the PCPs/FCPs of Philips DAP two different types of tests can be distinguished; development tests and release tests.

The objective of the development tests is to acquire knowledge. A designer from one of the innovation development departments consults the DQD to obtain information about a specific solution he wants to use in the shaver. This can imply the comparison of different new materials, lacquers, etc., the accordance to specifications of a new component or the evaluation of a proposed solution to a known problem.

Next to these development tests, DAP uses a release program that tests the shavers in an extensive way. In the definition phase of the PCP, one of the release engineers is appointed as the project owner; he enlists the specialists at the innovation group to draw up a first version of the test plan. This test plan is based on the product properties of this specific new range of shavers. When the shavers satisfy all the requirements that apply for the different tests it can be released to the next phase of the PCP.

Both the development as the release tests are based on tests specified in the General Test Specifications Shavers (GTSS). The GTSS is the collection of all the tests defined by Philips DAP and the result of many years of product testing. In case of new functionalities new tests are developed and added by the innovation engineers. Yet this results in an ever increasing number of tests, growing to unmanageable proportions. The GTSS is divided in a number of different chapters with per chapter a different category of tests. To provide a more detailed insight in the quality and reliability evaluations that are executed by the DQD during the PCP, first a description of the different test categories will be given and then their place in the development process plus the information they provide will be evaluated.

### 3.5.1 GTSS

- **Internal and External regulations**

These tests are aimed at demonstrating the shaver and the test programme do satisfy several internal and external regulations. The internal regulations concern subcontracting of tests that cannot be performed in-house, equipment documentation and calibration and filing of test results. External regulations relate to the demands made by authorities like KEMA, IEC and UL. These demands involve particularly safety and environmental issues.

- **Function**

The purpose of the functional tests is to determine the operating quality of the shaver in general and the shaving quality in particular. Besides, the sound power level of the operating shaver will be determined under different conditions.

- **Accelerated Field Test**

During the accelerated field tests the shavers are subjected to real customer use. In the marathon test shavers are used by several Philips employees each day in a specially equipped in-house shaving salon. In the consumer test the shaver is given to a home placement panel. On a regular basis the participants fill in a survey on their satisfaction with the product and problems they encounter. At the same time measurements are done on the shaver to get an impression on how the product will behave in the real market. Also the effect of human use on the soiling of the appliance is tested. The tests in this category are done by the Application Research Centre (ARC).

- **Life Tests on Electronics**

The cluster 'life tests on electronics' consists of several tests that simulate different conditions that the electrical part of the shaver could be subjected to during its life in the market. In the static life test the shaver is operated in on/off cycles for the specified lifetime while applying different loads to simulate shaving torque. During the test data on RPM and electrical current is logged and analysed in accordance to reliability. Other tests that belong to this category are: test on mains pollution, charge/discharge test, continuous charge test and a rechargeability test on different temperatures.

- **Climatic Tests**

The collection of climatic tests simulates the different climatic conditions the product, packaging and accessories could be subjected to during its lifecycle. The cyclic humidity test subjects the object to varying temperatures and humidity conditions and is also used as a corrosion test on metals. The constant humidity test simulates a subtropical climate. The thermal shock test subjects the product to rapid changes of ambient temperature. Similar are the cyclic heat test and the constant heat test. After the aforementioned tests the shavers are judged both functional and visual by means of a standard checklist. Two other but different climatic tests are the salt spray test and the light fastness test. The salt spray test, tests the resistance of the product for salt mist. The light fastness test determines the sensitivity to discolouration of the shaver and packaging when exposed to sunlight behind a shop-window.

- **Chemical Tests**

By means of the chemical tests the resistance of the housing, lacquers and decoration to lotions, cleaners and artificial is determined. After the prescribed testing procedure a visual and functional check is performed. Other tests that belong to this chapter are an adhesion test for double-shot products (hard foundation with soft layer), a swelling test for rubbers and a wear-out test for rubbers.

- **Resonance, Shock, Drop and Transport Tests**

In the resonance test it is checked whether or not the shaver can stand the resonance it will be subjected to during customer use. The single piece shavers are tested in the 3 possible directions with an increasing frequency for a fixed time. The transport test is similar to the resonance test except the shavers now are packed in the boxes they will be transported in. The shock test attempts to simulate the user putting down the product, corresponding to 7 years of use. Drop tests are carried out to simulate the shaver, single piece packaging or multiple packaging being dropped during transport or use.

- **Additional Tests Washable Shavers**

To assure that the washable shavers are watertight and that no safety issues will arise due to the combination of electricity and water some additional tests for this type of shavers are performed. There are three different tests where the shaver is immersed in water; the difference lies in the stress that is applied. One test uses soapy water, the second immerses the shaver in a 1-meter-deep water-column to increase the pressure on the appliance and the last one uses water of different temperatures to create an under pressure and water is sucked into the leaky shavers. To determine if the shavers do have a leakage they are weighed after the test and in case of a specific increase in mass, the leak is tracked down.

- **Additional Tests on Parts and Subassemblies**

Unlike the preceding test categories, which are all focussed on the complete shaver with all its functional and visual aspects, this chapter of the GTSS consists of tests to separately assure the quality and reliability of different parts, modules or subassemblies of the appliance. A substantial part of these tests are the so-called accelerated field tests or accelerated life tests (ALT). In these tests the entire lifecycle of a certain function is simulated in a limited space of time. Based on the specified lifetime of 7 years and the assumption of one shave a day this for example leads to switching the on/off button for 3000 times. Other tests enclose chemical, climatic and functional evaluation of functional blocks.

- **Measurements**

Next to the tests, which try to simulate various conditions the product encounters during its lifecycle, a great number of measurements are done on the shaver. On the one hand these measurements quantitatively express usability and functionality aspects of the appliance. For example the operating force necessary to switch the shaver on and off, the stroke of the trimmer, sound power levels or RPM of the cutter. On the other hand there are a number of measurements that determine the forces required to let the shaver fail such as the push in force of the LCD-display window or the pull out force of the on/off switch. Most of these measurements are done as well 0-hour as after relevant tests that may have affected the result of the measurement. The results of the measurements are used to make a statistical distribution and check if this distribution falls between the upper and lower limits of the specifications.

As mentioned above both the development tests as the release tests are based on the tests as described in the GTSS. The objective of (most of) these tests is to confirm that the shaver is able to meet specifications. The tests are designed for verification and or validation purposes. The verification is to assure "the product has been built right" from one development phase to the next. On the contrary validation is to assure "the right product has been built" [Bas03]. The existing tests use one stressor and this stressor is applied based on the product's technical specifications. In practice there are many stressors that act upon the product and that may influence the occurrence of failures. These stressors may or may not have a contribution, independently or in interaction to the occurrence of failures. The existing tests are not designed for product improvement and optimisation and are not able to find all product flaws and weaknesses. Therefore much more money is spent on products that fail in the market than Philips DAP would prefer. Besides there is spent a lot of time 'fire-fighting', solving unexpected problems in production and the market.

Applying only one stress each test also results in a great number of different tests as can be seen in the above description of the GTSS. In combination with using statistical quantities for each test this leads to a very large number of shavers needed to carry out the testing, resulting in high costs. To illustrate this, the test plan of recently released family of high-end washable shavers was observed. This range is composed of six types differing in information display (LCD, LED), lacquering, battery type and accessories. This test plan included a total of about 90 different tests, resulting in approximately 1700 shavers needed. These shavers were distributed as follows over the different categories of the GTSS; Internal and External regulations 2,2%, Function 0,7%, Accelerated Field Test 5,7%, Life Tests on Electronics 13,3%, Climatic Tests 12,6%, Chemical Tests 10,Resonance, Shock, Drop, Storage and Transportation 26,6%, Additional Test on Washable Shavers 4,0%, Component Tests 19,4% (8,8% shaving heads, 2,5% shaving units, 0,4% protecting cap, 0,6% trimmer, 0,3%

Motors, 0,2% Switches, 4,1% Painted housing, Prints, Etc., 1,1% Cord, 0,5% Case/Pouch, 0,9% Charging Stand) and Measurements 4,9%.

### 3.5.2 Place in the PCP

For a good assessment of the current test program, the content of the different tests as well as the timing in the design process where these tests normally take place is of significant importance. It is said 'normally' because not all the design projects are identical. In case of derivative PCPs for example not all phases of the standard PCP are (completely) passed through. Next to this, the test plan depends to a certain extent on the complexity of the design, for less complex designs not all tests are planned.

In figure 3.9 the current position of both the development and release tests is reflected. As can be seen the first tests do not start before First of Samples (FOS), a main event on the project's critical path, is passed. FOS is situated about halfway the PCP, approximately a year after the start of the project and a year before product launch. The reason why tests only start at this point in the PCP is that, from this moment on, test models are available, which are made with the same tools and moulds as the ultimate products will be made with. All functional blocks are put together and the shaver is working properly for at least sometime. The most important reason for not testing earlier is that it is thought that it is not useful to search for reliability weaknesses in a design that is still going to be changed. Those weaknesses might not exist anymore or be solved anyway if design changes are made later on.

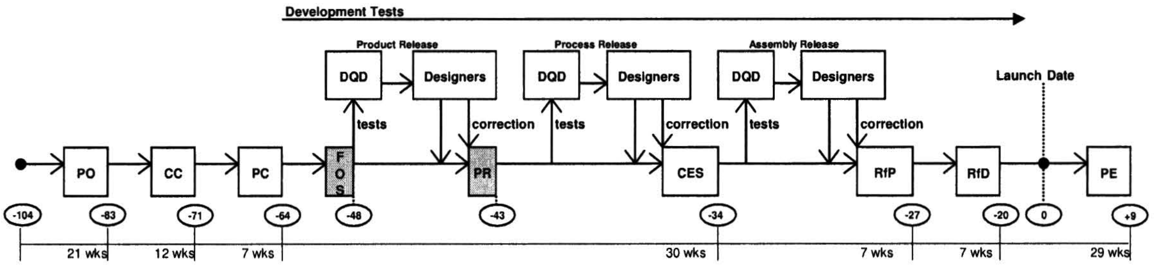



***Figure 3.9 Current Test Timing***

Despite the fact that the existing tests are success-oriented verification/validation tests and not designed for provoking failures, information comes available on components or functions that do not fulfil the specification set. These deviances are communicated to the relevant development department(s) and management. Designers have to take care of improvements of the design in those problem areas. At the same time the call-rate specialist at the DQD makes a prognosis of the expected effect of the problem on the field call-rate (FCR). Because the information on reliability of the design is provided rather late in the product creation process, changes to the design are time-consuming and expensive. In addition, these late design changes reduce the value of the foregoing release tests. Often, the end of the design process is hectic. Information on reliability problems becomes only then available and the market is already screaming for the products. The time pressure to solve these problems as quickly as possible is very high. When there is no suitable solution found for the problem before the next milestone meeting and the expected effect on the FCR is relatively small a dispensation can be written. If there is still no solution when the design is transferred to mass-production the dispensation is changed into an acceptation.

### 3.5.3 Conclusion

Philips DAP has an extensive test program based upon more than 65 years of experience in producing electric shaving appliances. During testing many different aspects of quality and reliability of the shavers is checked and a lot of statistical information on the performance of the shavers is gathered. This way of working satisfies when shavers are developed that use mature proven technologies, components and building blocks and when it is exactly known how the products are going to be used.

However, due to an increasing innovation speed on today's markets of high-volume consumer products the shavers are changing faster than ever. This innovation speed combined with a pressure on the time-to-market brings about a large number of risks and uncertainties regarding the behaviour of new shavers in the field. Therefore there is a need for analysis tests early in the PCP that are able to find all possible weaknesses in a product and thus reject or confirm these risks so that the product can be optimised.

# 4 Research Methodology

In this chapter, the project will be defined. The domain in which the research is positioned will be discussed, followed by the project formulation and the structure of the report will be outlined.

## 4.1 Problem Area

Because this assignment is executed in the field of research of the sub-department "Quality and Reliability Engineering" of Eindhoven University of Technology the general research objective will correspond to that formulated in [Qre04]:

***"To control and improve the quality, reliability and safety of products, by improving the performance of the relevant technical-operational business processes"***

In this case the 'relevant technical-operational business process' corresponds to the time-driven product creation process at Philips DAP Drachten. The goal is to control and improve the quality, reliability and safety of next generations of shavers created by that division of Philips. To achieve this goal the role of the development quality department (DQD) has been analysed. As already remarked in the first chapter, the responsibilities of the DQD can be split in two main activities:

- Collecting, analysing and classifying data from the field and from mass-production in behalf of corrective actions for production and preventive actions in behalf of development and projects.
- Product, module and component release through product testing based on both the Product Creation Process (PCP) and the Function Creation Process (FCP).

As the theory from chapter two already showed, these processes are strongly mutual dependent. From the analysis of the current situation in chapter 3 it can be concluded that both the testing activities and the field feedback activities in the PCP of Philips DAP have their strong and their weak aspects and offer opportunities for improvement. Because the cost of design changes after design release are very high and the customer satisfaction is negatively influenced if problems come up in the field, the focus will be on feedforward reliability control through testing. The general research objective for this research then is stated as follows:

***"To control and improve the quality, reliability and safety of electric shavers developed by Philips DAP Shaving Drachten by improving the performance of the quality and reliability control activities of the Development Quality Department"***

Analysis of the current role of testing at Philips DAP in chapter 3 has pointed out a number of problems/weaknesses that in the future could result in major threats. Summarized the recognized problems are:

- The information that the existing tests provide is interesting, but reveals only problems that come up under conditions that are based on the design specifications applying one stress at the time. Because the electric shaver is a high volume consumer product there is a great variety in customers, their behaviour and the environmental conditions the product is expected to operate in. Therefore the specifications do not have to reflect all possible circumstances the shaver could encounter in the market. Moreover the customer will also complain if the product fails outside of these specifications. Secondly, the greatest part of the tests are success-oriented they try to prove the product fulfils the design specifications. This obviously is important, but it does not give an insight in the strength of the design. It is more interesting to understand what the margins of the design are and if there are any weak points just outside of the specifications. Based on this kind of information designers are able to remove or strengthen these weak links and thus optimise the design.
- The information on quality and reliability of the design that is useful for product improvement is provided late in the design process. Information from tests that is useful for quality and reliability evaluation is provided only about halfway through the PCP. As discussed before, changes are least time-consuming and least expensive when they are made at the earliest possible stage in the design process. Therefore changing the design at that moment will be more time-consuming and more expensive than necessary.

- Because most of the existing release tests apply only one stress on the product. This is not a realistic reflection of the utilisation of the shaver at the customer and interaction effects of different stresses might be overlooked. Besides in combination with the statistical quantities used this results in a large number of different release tests and with that a large number of appliances needed, resulting in high costs.

- The existing tests do not make use of pre-selected prototypes. Therefore no potential sub-populations of extreme product-user interactions are examined and the existing tests do only test for phase 3 and 4 failures whilst phase 1 and 2 failures are getting more important for today's high-volume consumer products.

Based on the above it appears that by improving the reliability testing program in the PCP, improvements in reliability control can be realized. Resulting from this, the following general research question can be formulated:

***"How can the quality, reliability and safety of future generations of Philips electric shavers be controlled better by doing the right tests, providing the right information at the right moment in the PCP?"***

To overcome the imperfections of the current test program a new reliability test method should fulfil the following requirements:

- Design errors are detected by reliability tests as early as possible in the design process, so that design changes can be made when they are least costly.

- Besides detecting existing design errors, also expected problem areas in a design, the weak links in a design, are identified to which designers can react pro-actively.

- The reliability tests method should concentrate on the first three phases of the roller coaster curve described in section 3.1.

To meet the abovementioned demands it was observed in chapter 2 that next to the traditional success oriented validation tests that aim at showing how good the product is there is a need for so-called failure oriented analysis tests that are aimed at finding weak points in a specific design and can be applied in early phases of the PCP on both sub-assemblies as prototype models. Leading to the eventual central research question:

***"How can failure-oriented analysis tests be executed in the early phases of the PCP of Philips DAP that are able to find all design errors and weak links in a design?"***

As discussed in section 3.1, phase 1 and 2 failures happen mainly within sub-populations of extreme products, extreme users or a combination of both. To be able to identify these relevant sub-populations it is essential to learn from feedback information on previous products. Therefore an additional research question is formulated:

***"In what way can available feedback information be utilised better to analyse failure mechanisms, replicate failures in tests and identify relevant sub-populations of extreme users/products?"***

To answer those two research questions in the next chapter first literature is reviewed on different dimensions of failures, failure mechanisms, accelerated stress testing strategies and Design of Experiments.

## 4.2 Report Outline

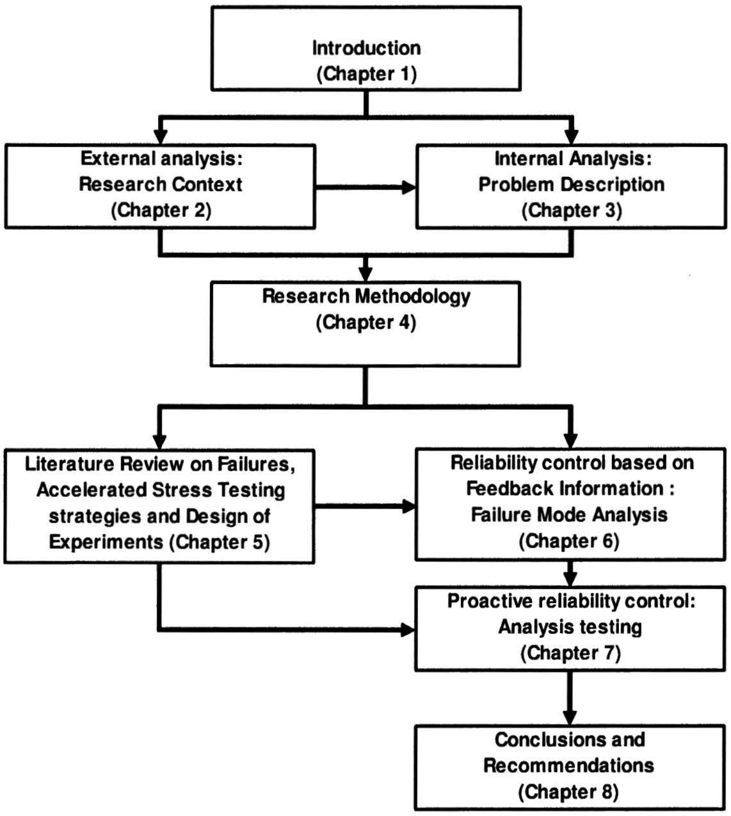



***Figure 4.1 Report Outline***

# 5 Failures and Accelerated Stress Testing

In this chapter first the background of product failures will be investigated by a literature review on the different aspects of this topic. The second section will explain the principles of Accelerated Stress Testing (AST), which is a promising solution to the challenge of executing a failure-oriented analysis tests, and review different AST-strategies. Then the third section deals with variation and Design of Experiments.

## 5.1 Failures

From a customer point of view the principal reason to report a (reliability related-) complaint is that, at a certain moment in time, there is a mismatch between customer requirements and the product performance. Although from a customer perspective all instances of such a mismatch will be grouped under the denominator 'Reliability Problem' there can be a large number of, fundamentally different, processes leading to such an event [Bro04].

### *5.1.1 Failure dimensions*

A common approach is to assume that the product fails at the moment it does not meet its specifications. There can be many reasons for such a failure. One of the most common classes of failure is the so-called 'physical failure'. Depending on the nature of the failure mechanism these failures can have a time-independent random character or can be time or use dependent, if mechanisms involve some form of wear [Lew96].

The so-called 'functional failures' is a second group of failures. These kinds of failures arise in situations where the product does not meet customer requirements in spite of the absence of physical failures. Conceptually, this type of failure can have two different causes. Either the product is, for other reasons than physical failures, not able to meet specifications or there is a mismatch between specifications and customer requirements. Therefore a distinction is made between:

- ***Hard reliability problems:*** Situations where the product is not able to meet both the explicit (technical) product specifications and customer requirements [Bro04].
- ***Soft reliability problems:*** Situations where, in spite of meeting the explicit product specifications a customer explicitly complains on the (lack of) functionality of the product [Bro04].

The third and last group of failures recognizes that statistical differences in products and differences in users have to be taken into account. If, with respect to time related effects, user profiles influence the degradation rate some products will have different failure characteristics than others. Also product internal aspects, such as product tolerances, can play a role. In case of soft reliability problems no explicit specifications are violated and therefore the situation that causes a customer complaint may differ from product to product and from user to user.

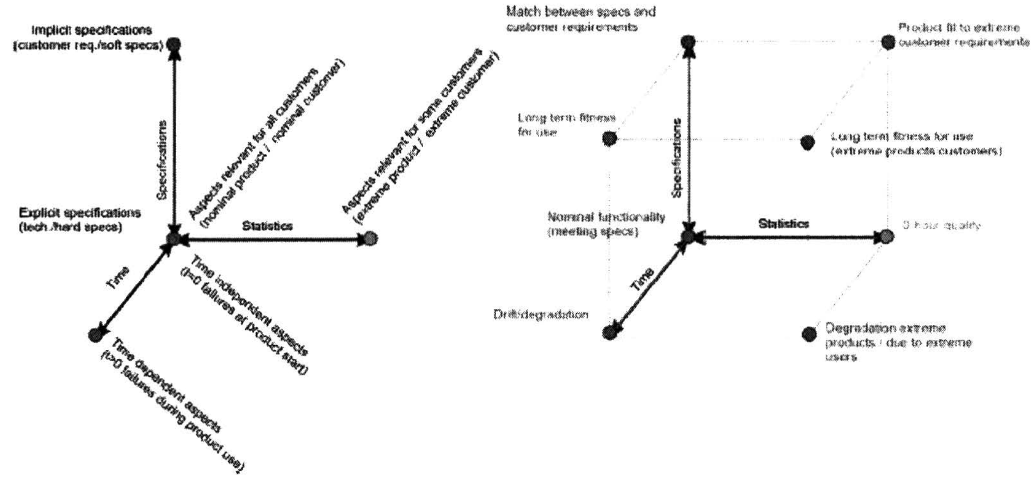



***Figure 5.1 Different dimensions of reliability problems [Bro05]***

With the different aspects of failure as mentioned above, three dimensions can be established and graphically represented as in figure 5.1.

### 5.1.2 Failure mechanisms

This research concentrates on physical failures. In the case of physical failures it is assumed that a product consists of components and that a failure happens when a (physical) gradual or instantaneous change occurs in a component. If such a component fails and this failure is not covered by some form of redundancy, the entire product will fail. The process resulting in a failure is called the failure mechanism. Failure mechanisms are related to the way components are used, the physical structure of the components and other internal and external influences relating to the probability of failure of a component. To analyse the influences of the various mechanisms on the lifetime of a component, Brombacher [Bro92] introduced the term stressor:

***"A stressor is a physical entity influencing the lifetime of a component or circuit."***

With the term stressor defined, the definition of a failure mechanism becomes [Bro92]:

***"A failure mechanism is a physical degradation process of a component influenced by one or more stressors."***

The probability that a component or circuit will fail due to such a failure mechanism not only depends on the external stressor(s) but also on its internal properties that stipulate the susceptibility for these stressors. Susceptibility can be defined as [Bro92]:

***"The probability function indicating the probability that a component will not remain operational for a certain time under a given combination of stressors."***

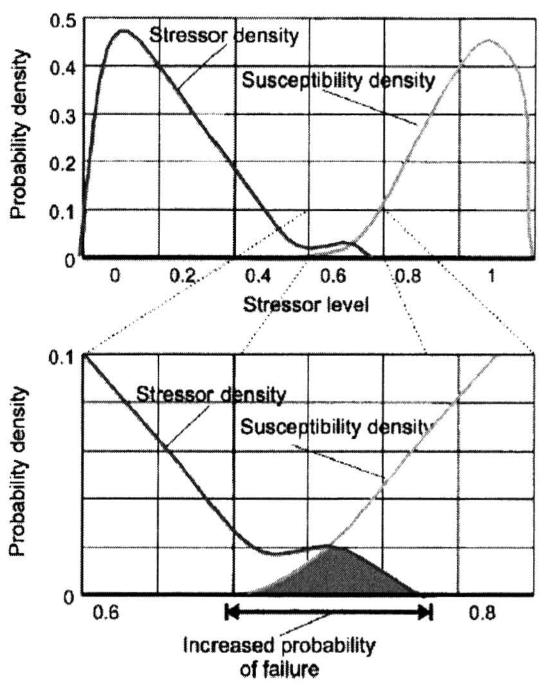



***Figure 5.2 Stressor/susceptibility concept***

To compare different stressors it is necessary to introduce a comprehensive stressor characterisation. For this purpose the term stressor probability density function is introduced [Bro92]. The main purpose of this term is to characterise the stress related to a certain failure mechanism. The same holds for the susceptibility characterisation. In figure 5.2 these two terms are combined and graphically represented. The grey area where both curves overlap indicates there is an increased probability of failure.

In the following illustration the stressor-susceptibility concept is used to explain the four-phase rollercoaster failure-rate curve, discussed in section 3.1, which models product behaviour in the field.

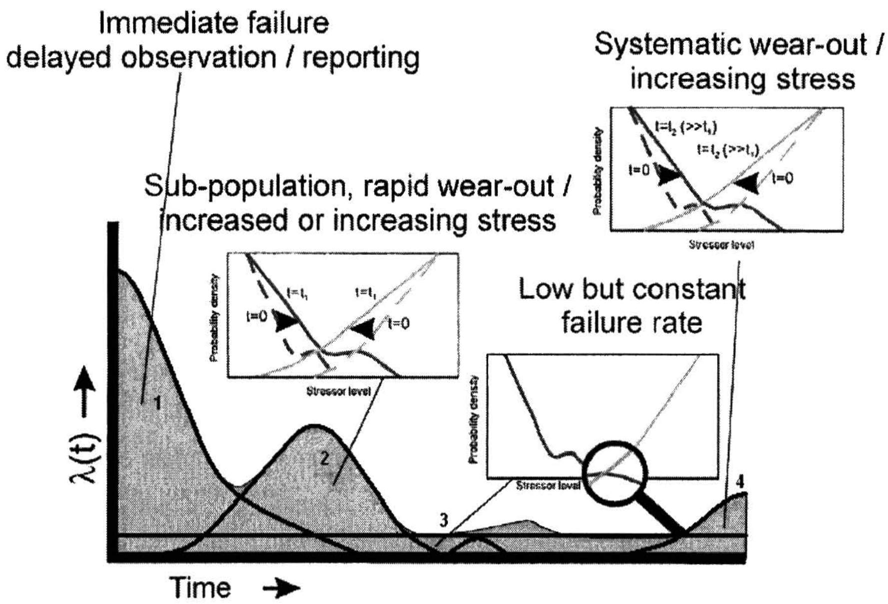



***Figure 5.3 Four-phase roller coaster failure rate [Luy00]***

## 5.2 Accelerated Stress Testing

As already observed in chapter 2, for a time-driven PCP both validation test and analysis tests are required to optimise product design and confirm the product's quality and reliability. A classical solution is to use accelerated stress testing (AST) to find reliability problems in products already during product development. In the following paragraphs, first the principles of test acceleration are explained, and then a number of AST strategies are reviewed.

### *5.2.1 Accelerating principles*

Accelerated testing is a method to activate product failures faster (and cheaper) in a well-controlled environment at the early stages of the PCP. There are two common principles, based on the 'stressor-susceptibility' concept, which can be followed to speed up the failure mechanisms. These common strategies are: increased probability of extreme stress and increased level of extreme stress. Both principles will be briefly discussed here:

- ***Increased probability of extreme stress***

The first strategy is to increase the probability of the occurrence of the failure by increasing the frequency of the real but extreme stress conditions of the field or by increasing the operation cycles of the product under test conditions given that the failure mechanisms remain the same for both the test and the field (figure 5.4). This strategy requires the knowledge of real but extreme stresses and the frequency of the occurrence of the extreme stresses. The advantage of using this strategy is that products are tested under real but extreme operating conditions and that translation from testing conditions to actual field conditions is relatively easy [Luy00].

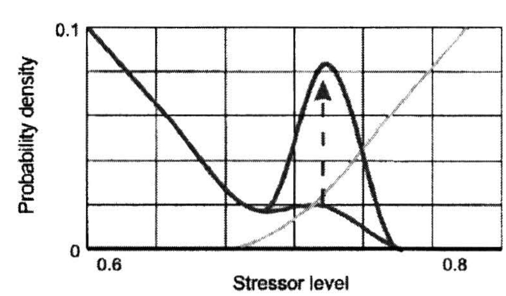



***Figure 5.4 Increased probability of extreme stress [Luy00]***

- ***Increased level of extreme stress***

The other strategy is to increase the severity of the real but extreme stress; given the failure mechanisms remain the same at both field and test (figure 5.5). This strategy also requires the knowledge of the stresses and their relevant ranges to evoke the same failure mechanisms. It is very easy to perform in practice. However, a strong understanding on the stress severity is necessary to maintain the link between the test and reality [Luy00].

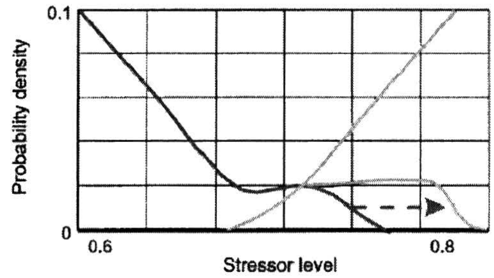



***Figure 5.5 Increased level of extreme stress [Luy00]***

Based on the idea of the stress-susceptibility interaction there is still a third strategy that could be used. It is to decrease the product strength so that normal stress acts like extreme stress. The probability of having a failure is also increased this way. However, the disadvantage of such a test is that it is very difficult to design and perform in practice and therefore will be disregarded for the rest of this thesis.

### 5.2.2 AST strategies

As already observed in paragraph 2.5 an analysis test is a 'failure oriented' test as early as possible in the PCP. It aims at reducing uncertainty by confirming or rejecting risks that may or may not happen in a future product. It is meant to invoke realistic product failures early in the PCP and to detect as many failures as possible. Then control loops and follow-up actions could be taken to prevent and control those potential failure mechanisms. To activate failure mechanisms faster (and cheaper) accelerated stress testing is used. In this section a number of AST strategies are reviewed.

The classical AST tests products according to a commonly accepted test standard/generic list against the constant failure rate model [Luy00]. The use of a generic list to conduct AST has a number of known risks. It could be possible that unrelated failure mechanisms might be activated, irrelevant stresses might be used, or test results might be interpreted wrongly without the knowledge of the genuine failure mechanisms that may happen in the field [Luy00]. That is, classical AST only tests for the constant failure rate with poor correlation to the actual product field performance. Next to this classical AST strategy there are some very recently developed AST strategies, i.e. Highly Accelerated Stress Test (HAST), Multiple Environment Over Stress Test (MEOST).

- *HAST*

HAST tests products under a condition where a single stress is increased step by step until its susceptibility limit is reached and a failure occurs. From the test results possible rating or derating could be determined. The main risk is to activate failure mechanisms that are irrelevant and will never occur in practice. Moreover the possible interactions between different stresses that might be valid in the field are ignored [Luy00].

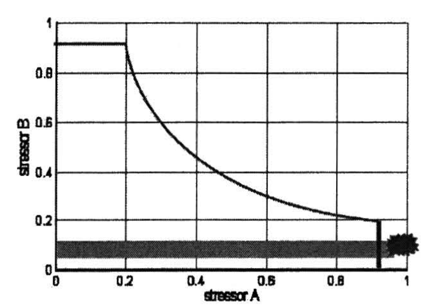



***Figure 5.6 HAST [BdO00]***

- *MEOST*

MEOST tests products by increasing stress step by step for several combinations of stressors until a failure mechanism is activated. To perform MEOST requires the knowledge of relevant failure mechanisms in the field, stresses and interaction among those different stresses. It also requires many in-house experimenting [Luy00].

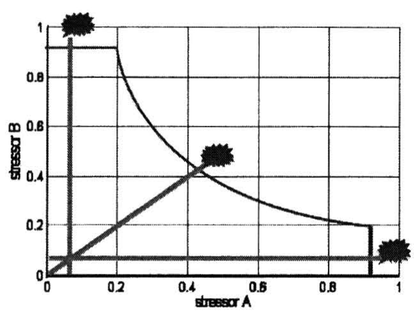



***Figure 5.7 MEOST [BdO00]***

Though, Lu et al. [Luy00] observed that all the above AST strategies use generic lists and there is lack of distinct knowledge of failure behaviour of (sub-) populations of products. The use of such AST strategies lead to low predictability during the early stage of the PCP because irrelevant failure mechanisms may be tested under irrelevant stress profiles and test results may be misused to predict the product field performance.

From the foregoing it can be concluded that the classical AST strategies do not correspond with the failure mechanisms that arise in the field. Lu et al. [Luy00] suggest a naturally arising alternative to the classical AST that tests the product against failure mechanisms identified from the analysis of the physics of the field failures. This strategy is called 'Physics of Failure' strategy. It requires the knowledge of the relevant failure mechanisms, product susceptibility, product specifications, interaction between different failure mechanisms, etc. Keeping in mind, not all users are the same resulting in different stress levels, not all products are the same so strength is product related and even if all products would be the same then not all products would remain the same. Therefore when performing AST a different strategy should be applied for each of the four phases of the roller coaster curve.

***Phase 1*** failures happen when the product does not fulfil customer specifications, is not caught by the test program or just fail after tests are performed. The recommended approach is to identify the failure mechanism, identify the relevant sub-population of products and identify the stress level for this sub-population. Then the idea is to pick out this sub-population of products under a test program, in which the identified relevant stress is applied before sending them to the customer.

***Phase 2*** failures happen when products are delivered with either increased stresses, due to e.g. material tolerances or tolerances in use) or component flaws leading to rapid wear-out. It is almost impossible to test for phase 2 failures in production since the failure can only be triggered when high stresses are applied. So the appropriate way to tackle phase 2 failures is to build special analysis prototypes for this sub-population and test them by either increasing the stress levels or by increasing the likelihood of the extreme stresses early in the PCP.

Next the ***phase 3*** random failures, which appear in the complete population and will result in a failure probability that is to a certain extend constant in time. These failures are mainly due to customer use and external random effects. Those operating conditions should be simulated on prototypes to increase the likelihood of detecting product failures at the early phases of the PCP. Then the results should be interpreted and if considered necessary design improvements can be made to optimise product reliability.

***Phase 4*** failures are the result of natural wear-out of design and material due to customer use. The failures are similar to these of the second part of the roller coaster curve but now apply to all products. Analysis prototypes that represent the entire population are to be tested under the elevated identified relevant stress levels at the early PCP.

Summarizing this part, this leads to a picture such as has been reflected in figure 5.8.

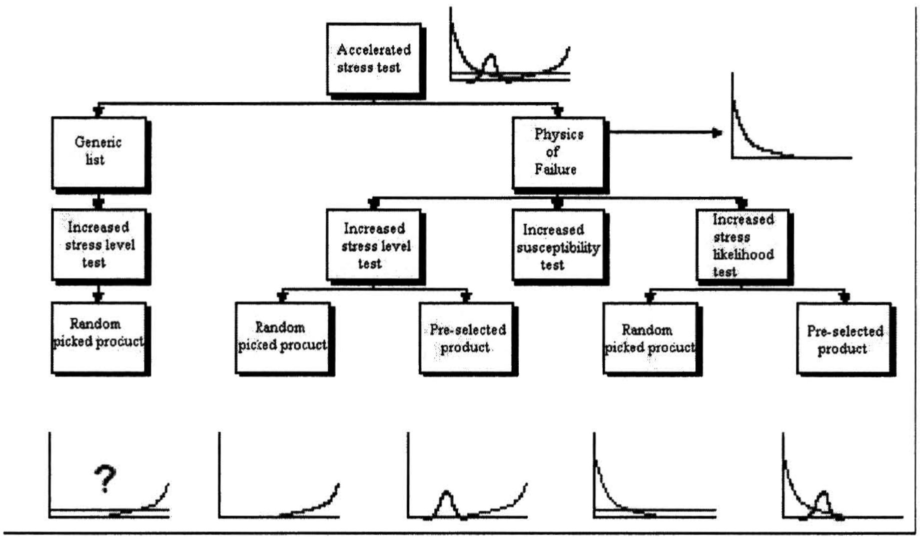



***Figure 5.8 Strategies on accelerated stress testing***

## 5.3 Variation and Design of Experiments

To be able to optimise the product in the early stages of the PCP an increasingly important aspect to be considered is variation. When dealing with high-volume consumer products such as electrical shavers there is a situation where both no single product is exactly the same and no consumer uses the product in exactly the same way, resulting in an uncertain distribution of respectively strength and load (figure 5.9).

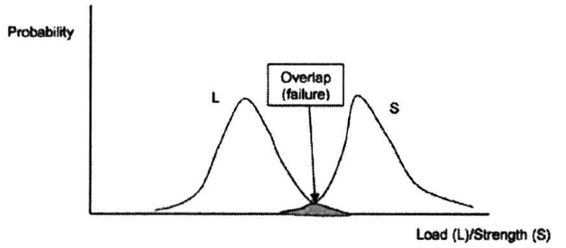



***Figure 5.9 Load/strength var. [OCo01]***

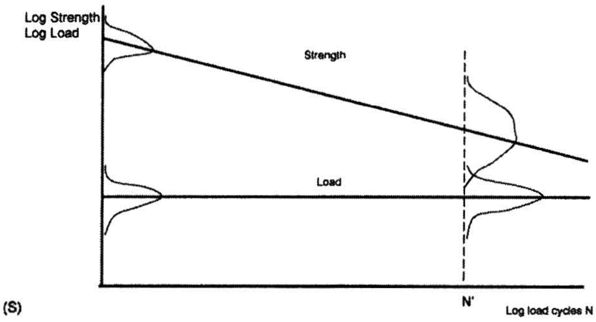



***Figure 5.10 Time dependent var. [Oco01]***

However, variations of parameters in engineering are not always constant in time. Manufacturing processes might vary from batch to batch, from day to day, from supplier to supplier, etc. Application environments might change if there is a change of use. A very important category of change is that of strength as a result of any or a combination of the many conditions that can cause weakening during use. In these cases the initial strength might be adequate but it eventually deteriorates to the point that it can no longer withstand high values of applied stress (figure 5.10). Note that the distribution of applied load does not usually change, but the mean value of the strength reduces, while the spread increases.

So far only situations in which only one or two (load and strength) parameters are variable have been considered. However, in many engineering situations there are several variable parameters. A (sub)system generally will contain a number of components, each with variable dimensions or parameters and these might also vary as a result of temperature or other stresses. Some of the variables might have significant effects, other less. A particularly important aspect of multi-variable systems is that some of the variables might have effects that are interactive, so that their combined effects are significant. Sometimes interaction effects can be stronger than any single effect.

In any design in which performance, reliability or durability might be affected by variations, they must be included in the test programme [Oco01]. If only one or a few variations are considered likely to have significant effects, the effects are understood, and there are no interactions between them, then conventional one-at-a-time tests using the above AST strategies might be sufficient. However, if these assumptions cannot be safely made, then statistical experiments should be performed to determine which variations and interactions are significant, what the causes of the variation are and how variation can be reduced. The most powerful of the techniques to set up such statistical experiments is generically called the Design of Experiments (DoE). DoE is particularly important in two areas:

3. For resolving chronic quality and reliability problems in production and in the field (Chapter 6)
4. At the design stage of both product and process (Chapter 7)

The objectives in both areas are as follows:

1. Identify the important causes or variables – whether they be product or process parameters, materials or components from suppliers, environmental or measuring equipment factors
2. Determine the main effects and interaction effects of these important variables.
3. Reduce the variation on the important variables through close tolerancing, redesign, supplier process improvement, etc.
4. Open up the tolerances on the unimportant variables to reduce costs substantially [Bho91].

There are three approaches to the DoE: the classical, Taguchi, and Shainin. This last approach outdoes the other two in terms of effectiveness, cost, complexity, statistical validity, applicability and ease of implementation. The Shainin approach consists of seven DoE tools, clues can be gathered with each DoE tool, each progressively more positive, until the number one culprit cause – the Red X – is captured, reduced and controlled. Not long ago the seven 'Shainin' DoE tools were implemented by Philips DAP, so the content of the tools is supposed to be familiar, therefore the separate tools will not be discussed any further apart from an overview in Appendix H.

## 5.4 Conclusion

In this chapter from literature a number of concepts, methods and strategies concerning failure dimensions, failure mechanisms and testing were introduced. In the next chapter it will be determined whether using these tools enables root-cause analysis and reproduction of a reliability problem arising on the market which was not found in the current test program. The failure will be classified on the basis of the rollercoaster curve concept, the large number of factors possibly contributing to the occurrence of the problem will be reduced making use of several DOE-tools and finally the failure will be reproduced in an accelerated stress test based on the Physics of Failure (PoF) approach described in this chapter.

# 6 Reliability Control based on Feedback Information: Root-Cause Analysis an Experimental Case Study

In this chapter a failure, actually observed in the market, is selected and examined more closely. In the first section the failure is selected, described and classified on the basis of the theory discussed in the first paragraph of the previous chapter. Next, the Physics of Failure approach for this class of failure will be determined. All the available information is gathered and represented based on the DOE-principles described in the previous chapter. In this way conclusions can be drawn and the unmanageable large quantity of possible contributing causes can be reduced. Now the failure mechanism has become clear and it will be simulated using the relevant acceleration principles according to the PoF principle. This analysis has a dual purpose:

1. to show how available feedback information from production, tests and the market in combination with some relatively simple AST / DOE experiments can be used to identify failure mechanisms and their root causes in a structured way.
2. to identify the shortcomings of the current test program in order to propose a new approach for analysis testing in the following chapter.

Therefore the key success factor for this chapter is the replication of an existing market failure.

## 6.1 Problem Selection

It is quite difficult to determine what kind of product or assembly is to be used in the experiment, because there is no similar past experience that can guide the research. Therefore a product is chosen that could suffer an unsuccessful result, usually to be called NFF (no-fault-found), when testing with existing tests. The FCR is high enough to make a comparison with the actual field failures. Besides this, the product where this module fits in should be one that needed improvement. Based on these requirements the so-called 'nozzle' of the shavers from the Pluto-family (7740, 7760 and 7780) was chosen.

The Pluto is a product family from the 'additive' range. This range has been developed and introduced by Philips DAP to create a new market segment and attract wet shavers. These additive shavers are watertight so they can be used under the shower and have the special feature to apply moisturizing shaving lotion or gel (additive) on the skin during shaving. The backside of the shaver has a compartment (Appendix I - Photo1) where a cartridge (I - Photo2) with shaving lotion/gel can be put in. On to this cartridge the customer has to attach a pump (I - Photo3) that is supplied with each packing of cartridges. This altogether (Appendix J - Photo4) has to be inserted in the shaver (J - Photo5). Then the lotion can be pumped up by pressing the yellow additive knob (J - Photo 6).

The failed products that are returned from the market are unable to pump up additive to the shaving surface because the dosing nozzle (Appendix K) where the lotion should flow through is closed. When the customer pushes the additive button the moisturizing lotion ends up in the cavity of the additive button and eventually leaks out through the chink between additive button and nozzle or flows back into the cartridge compartment. This results in a messy shaver, no additive applied on the skin and a dissatisfied customer.

A remarkable issue is that in the predecessors of the Pluto-family, Aquarius, Neptunus and Cleo exactly the same soft-touch material was used to manufacture the additive button and the soft-touch outer layer of the nozzle, however within these product ranges there never has been a product returned that suffered from the same problem.

After closer examination of the failed products it could be concluded that plugging of the nozzle is not caused by external dirt (beard hair, soap, etc.) or drying up of the additive in the nozzle. The real reason for the flow blockage is deformation of the so-called 'soft-touch' outer layer material of the nozzle. This occurs such that the material closes slowly the end of the nozzle. This indicates changing material characteristics over time and the failure therefore can be classified as a phase 2 or phase 4 failure. On the outside no distinction can be made between those two phases, the main difference is the former only appears in certain extreme product-user combinations and the latter will eventually arise in all applications on the market. In order to determine the class of failure we are dealing with, the time to failure and FCR number will have to be analysed next.

Until this very moment the problem of the closed nozzle resulted in 18 returned shavers from The Netherlands, leading to a FCR contribution of approximately 0,08%. The time-to-failure distribution derived from the failure data by calculating the difference between date of purchase and date of failure report is represented in figure 6.1.

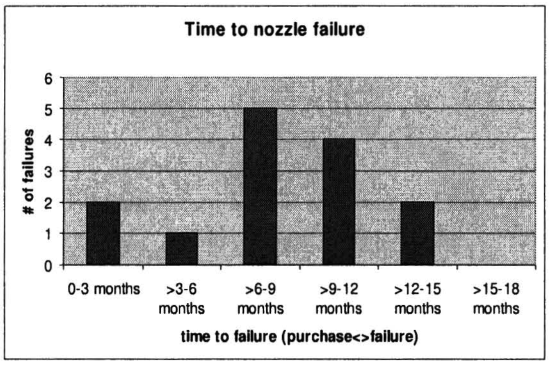



***Figure 6.1 Time-to-Failure***

From the data it can be observed that if the failure arises, this occurs on average 250 days after acquisition of the shaver. However, since the Pluto only was introduced in March of 2004 no data is available for products on the market longer than 18 months. Next to the failed shavers, there are thousands of shavers from the same family on the market that do not (yet) suffer from this problem, therefore it can be concluded we have to do with a phase 2 'early wear-out' class of failure. These failures are observed in distinct sub-populations of the product and are the result of extreme product-user combinations due to variations in the product characteristics, variations between users, variations in product use or a combination of the three.

Next to the failed products returned from the market, the problem is also observed in the in-house marathon shaving salon. Here Philips DAP employees can go to shave themselves with the newest shavers and at the same time valuable information can be gathered about for example ease of use, handling, shaving closeness and product reliability. The nozzle problem was detected in 100% of the 6 appliances used in the marathon shaving salon. In the shaving salon a standard procedure for using, washing and storing the shavers is applied (figure 6.2), therefore the number of possibly influencing variables regarding customer use is limited.

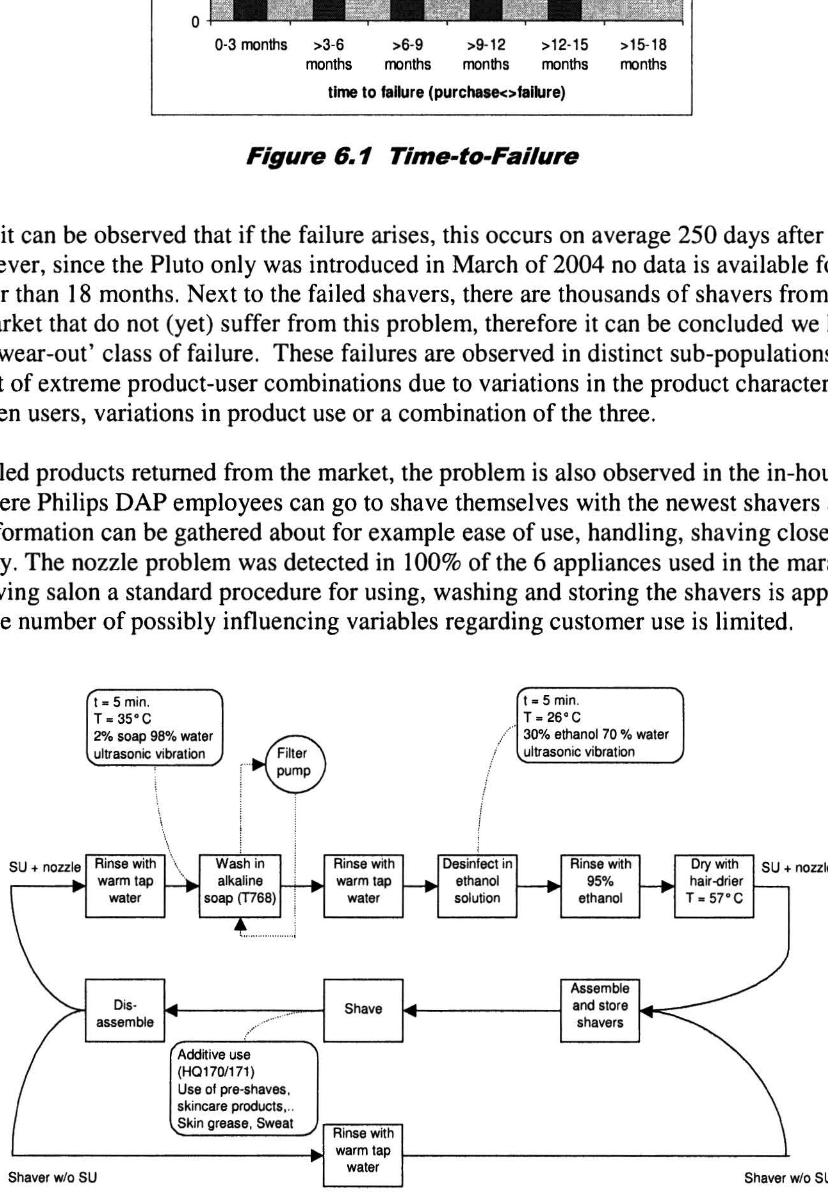



***Figure 6.2 Marathon Shaving Room Process***

The fact that the failure turns up in all of the appliances deployed in the marathon salon could indicate that we do not have to do with a distinct sub-population of products but the problem is eventually present in all shavers. But it is also possible that the failing nozzles from the marathon all are part of this relevant sub-population. So, on this point no conclusion can be drawn without further investigation. Therefore in the following section possible sub-populations of products will be further examined.

## 6.2 Sub-populations of Products

In this section it is examined if the problem is potentially present in all nozzles or only in certain sub-populations of weak products. To identify possible sub-populations of products, contrasting groups of products have to be put together after which these groups can be compared on occurrence of the problem. When there exist differences between distinct groups of products this is the result of variation in the production process or in that of the supplier. Bhote [Bho91] mentions six different sources of variation namely: poor management, poor product/process specs, poor component specs, inadequate quality system, poor supplier materials and operator errors.

### 6.2.1 Production Process

The nozzle is manufactured in a so-called hard-soft multi-component injection moulding process. In an injection moulding process heated plastic is forced under pressure into a mould cavity which is the inverse of the desired shape; it is then clamped together and solidifies into the shape of the mould creating the part. Multi-component moulding is a multi-step moulding process that produces an assembly, comprised of two or more integrated components. Hard-soft moulding is a variation of multi-component moulding and is used to give a certain part a gentler touch. The hard material is first injected into the cavity after which the mould rotates and the soft material is injected. In the case of the nozzle the hard material used is polypropylene and the soft material is SEBS (Styrene-Ethylene-Butylene-Styrene).

### 6.2.2 Multi-Vari Charts

To determine if there is a certain variation pattern involved in the occurrence of the failure, in this paragraph a number of multi-vari charts is created. According to Bhote [Bho91] there are three possible patterns of variation: positional, cyclical and temporal. These patterns will now be discussed one at a time.

**Positional**

Examples of positional variation are:

- Variations within a single unit or across a single unit with many parts
- Variations by location in a batch-loading process
- Variations from machine to machine, operator to operator, or plant to plant

There are three identical machines that are able to produce the product but only one at the time is operational because there is only one mould for this specific nozzle. So variation between moulds can be excluded. The mould has 8 different positions or mould impressions, so per cycle 8 nozzles are produced. To define if a certain position produces more failing nozzles the die cavity numbers of the failed nozzles were inspected. Unfortunately this number could only be determined from 7 (4 marathon + 3 field) nozzles. As can be seen in the following figure this did not reveal any striking abnormalities.

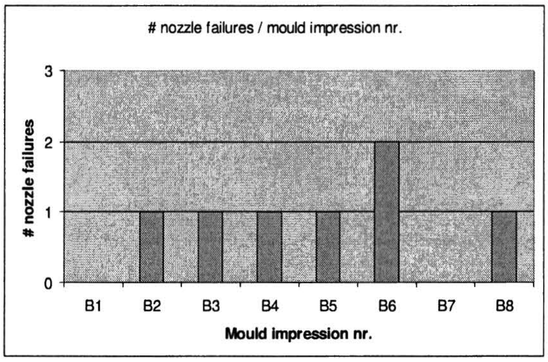



***Figure 6.3 # of failures per mould impression position***

Each nozzle has a mark indicating from which cavity of the mould it is originating; there is no information on which machine it was produced or which operator was operating that machine at the time of production. Therefore no further information of positional variation was available.

## Cyclical

Forms of cyclical variation are:

- Variation between consecutive units drawn form a process
- Variation among groups of units
- Batch-to-Batch variations
- Lot-to-lot variations

Its difficult to determine whether cyclical variation has an effect because: a) on the outside no perceptible differences can be observed between 'good' or 'bad' nozzles and b) no information on batches or lots is available on the failed nozzles. A possible distinction among groups of products can only be made on the basis of the three different types in the PLUTO range, the 7740, 7760 and 7780. The problem arises in all three types of the Pluto-family (figure 6.4). This seems reasonable because the additive button, nozzle and SU of the shavers are exactly the same. The only differences between the three types are in the colour, the information display (# of LEDs) and the battery type (1u/8u charging time, 55/45 shaving minutes). Therefore one would expect that the failure arises proportionally in each of the types. The sales quantities of 7740, 7760, and 7780 are approximately in ratio 10:6:7. Therefore the number of failures in the 7780 is higher than expected. There are two possible reasons for this:

1. The 7780 is the High-End appliance of the Pluto-family and therefore these customers could be dissatisfied and complaining sooner.
2. The other possible reason is physical, the 7780 is equipped with a 1-hr quick-charger and during charging the battery produces way more heat than the 8-hr slow-charger, so temperature could be an influencing variable.

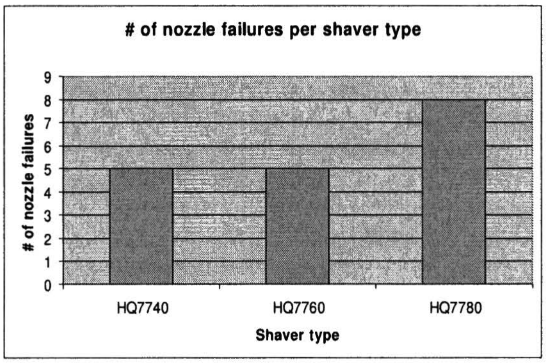



***Figure 6.4 Failures per shaver type***

## Temporal

Temporal variations are variations from hour to hour, shift to shift, day to day, week to week, etc. As already mentioned, from the outside of the nozzles no information regarding production time can be deduced. The only indication of time is the production week number that is printed on the shaver at the end of the assembly line. When the number of failures for each production week are presented graphically this results in the following figure.

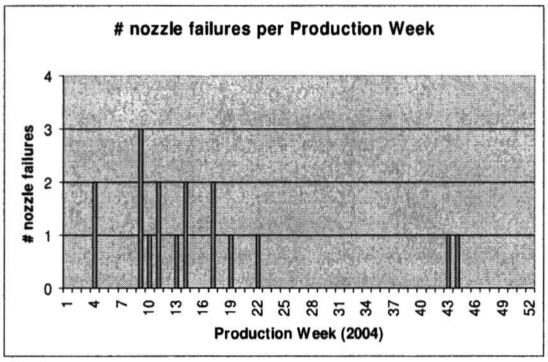



***Figure 6.5 # of failures per production week***

It is difficult to draw conclusions from the above figure. It looks like that especially in the first half of 2004 there could have been a problem in production. But this conclusion would be too premature. Because the production quantities are not the same in each week and larger in the first weeks after production start to be able to supply all sales channels. Besides, in week 31 t/m 34 there was a collective summer break so in this period there was no production at all. Based on the long pipeline between the end of the production line and purchase by the customer, as observed in chapter 3, it can be assumed that shavers produced in the last weeks of 2004 are still in this pipeline or too short in use for the failure to appear. Also, the number that refers to a certain production week is placed on the product in the end-phase of production and the inventories of parts such as that of the nozzle are not taken into account.

When cyclical or temporal variation between nozzles does exist, this could be the result of changed process parameters. The most critical process parameters in the hard-soft injection moulding process are:

- the temperatures, both of the mould and of the material before it is injected,
- the pressure with which the fluent plastics are injected into the mould,
- the timing of the different steps of the injection moulding process.

These parameters did not change in the past two production years for the PLUTO nozzle. Even the nozzles of predecessors AQUARIUS, NEPTUNUS and CLEO where produced in the same injection moulding process using corresponding parameters and never leaded to any call-rate.

Another possible cause for temporal or cyclical variation is changed composition of the raw material. However, the supplier of the raw material (CAWITON SEBS), Wittenburg BV, assures the composition of the material has not changed in the past two years. Additionally, the material quality was continuously monitored utilizing different analysing techniques.

So far the analysis did not reveal any clues for the existence of a sub-population of weak products. To confirm this supposition a closer look is given at the appliances put into service at the marathon salon. The nozzle failure was observed in 100% of the six shavers therefore all these nozzles should belong to the sub-population of weak products, if existent. When the production week numbers of the shavers is observed it strikes that all of these shavers are manufactured between 406 (week 6 of 2004) and 412. This means that all these products were produced in weeks that according to figure 6.5 are suspicious because they delivered more failing nozzles. Nevertheless no changes in production process parameters or deviations in raw material quality were observed since the start of production in the end of 2003. Therefore it seems rational, based on the components search principle [Bho91], to switch the failing nozzles from the marathon salon with new nozzles from a production week that is not suspected according to figure 6.5 to confirm all produced nozzles can be considered equal with regard to this particular problem and no sub-populations of weak nozzles can be distinguished.

The original nozzles were replaced after approximately 850 cycles in the marathon salon. At this point the nozzles were completely closed and no longer functional. After replacement of the 'bad' nozzles with 'good' new nozzles, the appearance of the new nozzles was monitored through taking pictures (Appendix L). On these photographs it can be clearly noticed that the problem also is present in the nozzles from the current production, after 693 cycles the nozzle is almost completely closed. The nozzles that were not photographed showed exactly the same symptoms. Therefore from now on it is assumed that there does not exist a relevant sub-population of weak nozzles with regard to this problem and all nozzles equally suffer from it. This implies that the failure mechanism is the result of the material properties of the SEBS material and caused by certain use/user characteristics.

### 6.2.3 Paired Comparisons

As described in the previous chapter, the paired comparisons method is similar to components search, with the objective of reducing a large number of variation down to the family of the Red X by providing clues derived from comparisons of paired 'good' and 'bad' units. First one 'good' and one 'bad' unit are selected. Then this pair is observed in detail to note differences between these two units. These differences can be visual, dimensional, electrical, mechanical, chemical, etc. Next a second pair is formed and again the differences are noted. This procedure is repeated until the observed differences show a pattern of repeatability.

As already mentioned earlier in this chapter, the predecessors of the PLUTO range, AQUARIUS, NEPTUNUS and CLEO, all had nozzles that were produced in exactly the same manner composed of exactly the same two materials. However, none of these types ever suffered from a similar failure neither in the market nor in the marathon salon. Because the PLUTO and AQUARIUS are both shavers from the additive segment serving the same markets, the set of consumers is assumed equal. Above it was observed that the failing PLUTO nozzles do not belong to a 'bad' sub-population. Therefore the explanation for the fact the PLUTO does suffer from this problem and the AQUARIUS does not, must lie in the differences in the design. So in this paired comparison the 'bad' unit is a PLUTO nozzle and the 'good' one is an AQUARIUS nozzle. To be able to identify all relevant differences, design drawings (included in Appendix M) of both nozzles were studied.

***Conclusion:***

- The PLUTO nozzle functions as a rotational axis; every time the SU is opened maximally, the nozzle is subjected to a mechanical stress. The AQUARIUS nozzle on the other hand rotates conjointly with the rest of the SU and does not experience any mechanical force.
- On the illustrations in Appendix M it is clearly perceptible that the soft-touch layer on the PLUTO nozzle covers the complete outside (1) of the nozzle and also the inside (2) of the opening. On the AQUARIUS nozzle the layer only covers the outside (3) of the nozzle and not the inside (4) of the opening.

The failure mechanism and distribution in time to failure however must be explained by means of use/user characteristics, these will be studied next.

## 6.3 Variation between use/users

Now it is clear that there are no relevant sub-populations of products, the root cause of the failure must originate from a certain stress or combination of stresses resulting from use/user characteristics. Every customer has its own way to use and handle the product, therefore some customers will uncover design flaws and weaknesses due to their way of using the product while others will not or substantially later. Because the problem arises in 100% of the nozzles that is put into service in the in-house marathon shaving salon it is certain the relevant stress or combination of stresses is present in the process the nozzle goes through here. Then the wide distribution in time-to-failure can be explained by variations between users in the level of the applied relevant stress(es) (figure 5.5) and variations between users in the probability of occurrence of this particular stress(es) (figure 5.4). The purpose of this section is to find this relevant stress(es) and to replicate the failure mechanism.

### *6.3.1 Stressors*

In the marathon salon the nozzle goes through a well defined process (figure 6.2). Therefore it is relatively easy to draw up a finite list of possible influencing stressors. To do this in an ordered and complete way the process is split up in three separate phases; shaving, cleaning and storage.

**Shaving:**

- Environment (shower, mirror, ... > humidity, temperature, ...)
- Frequency (shaves a week, # times using additive/shave)
- Use of additive, pre- / aftershaves, or other cosmetics. Contact with sweat and skin fat.

**Cleaning**:

- Frequency (after every shave, once a week, etc...)
- Temperature of water
- SU opened/closed, SU (not) disassembled, (not) tapped dry
- Use of soap, detergents

**Storage:**

- Environment (temperature, humidity)
- Position (in charging stand, side, SU opened/closed)

Although we have a limited enumeration of possible influencing stresses it is not possible to switch these separate stresses on and off to determine which stress is the main contributing variable, the red X. This would disturb the normal procedure in the marathon too much. And moreover this would take way too much time, since in the marathon salon a particular PLUTO is used at most 3 times a day, which would result in approximately a period of 1 year to failure. Therefore the collection of possible contributing stresses needs to be reduced. After which the relevant stresses can be applied using the physics of failure approach of accelerated stress testing to stimulate occurrence of the failure.

First telephone calls to some of the complaining customers were made to reveal possible extreme use characteristics. Unfortunately this did not disclose any unexpected use of the shaver. All questioned users did:

- Rinse the shaver with warm or hot water
- Not use any detergent or soap to clean the appliance
- Only use the supplied moisturizing lotion (HQ170, HQ171)
- Let the shaver dry with closed shaving unit
- Not use any pre-shave or face cream

However it is always uncertain whether an approached customer is completely honest about the way he handles the shaver anxious about being excluded from the guarantee package. Next to this a customer will only mention the aspects of use he is asked for and he considers relevant.

The fact that one individual user experienced the specific problem twice, supports the conclusion that the variation between customers or between the way customers use the product really does influence the occurrence of the problem. On a total of 18 products returned with this problem from a market with thousands of PLUTO appliances it seems statistically improbable that this is just by coincidence. Because during service only the failed part (pump slide/nozzle) is replaced, this could also indicate an interaction problem with other parts (SU) of the shaver.

Another aspect that may be interesting regarding the operational environment of the shaver, is the period of the year the product fails and is returned in. In the following figure the distribution of the 18 market returns over the four quarters of the year is represented.

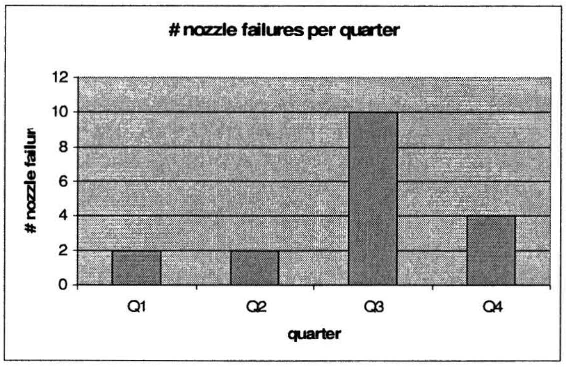



***Figure 6.6 # of market returns per quarter***

This histogram shows that over half of the products brought in with a closed nozzle were returned in the third quarter (July-August-September). Analysing the original data, it can even be seen that exactly half of all market failures where returned in July and August, which is significantly more than could be expected based on a uniform distribution. Possible reasons could be the higher temperatures in the summer, sweat, ultraviolet radiation in sunlight, suntan cream/lotion, etc.

### *6.3.2 Paired Comparisons*

As already applied in section 6.2.3, the paired comparisons has the objective of reducing a large number of variation down to the family of the Red X by providing clues derived from comparisons of paired 'good' and 'bad' units. In paragraph 6.2 it was concluded that variations between products do not play a part in the occurrence of the problem. Therefore all newly produced nozzles can be considered as 'good'. For the 'bad' units both returned market nozzles as nozzles from the marathon were selected. This has led to the following conclusions, all 'bad' nozzles:

- were discoloured
- had increased weight
- showed prints of the SU on both (left + right) sides
- were closed or had a strongly decreased diameter
- seemed to have a softer feeling and were less wear resistant
- looked swollen or bloated
- lost the ellipse relief at the top

Most of these differences were observed visually and are difficult to express quantitatively. An exception is the increase in weight of the failing nozzles that can be determined relatively easy. Therefore this number can be used to compare nozzles that were subjected to different (combinations of) stresses. This is done by clustering of nozzles used in a comparable manner, this way contrasts are created between these clusters and based on these differences certain conclusions may be drawn.

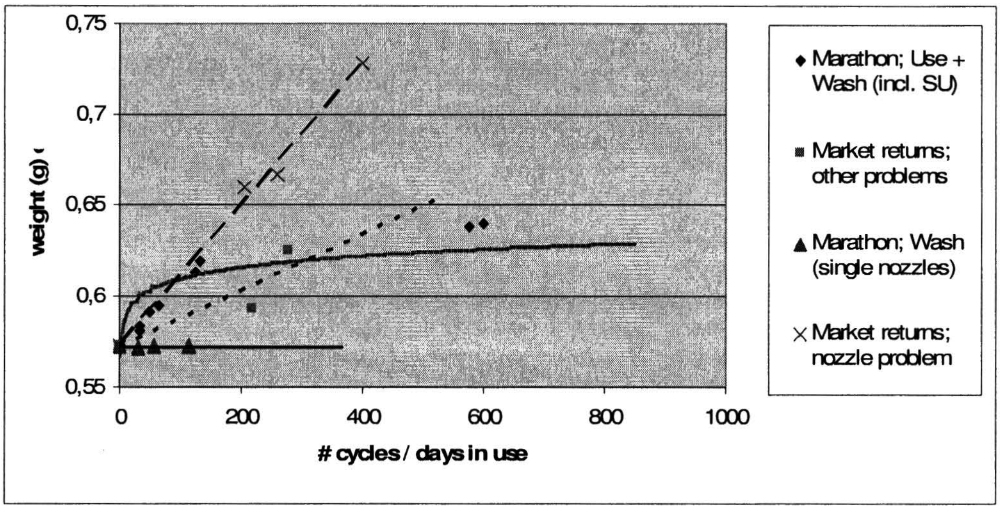



***Figure 6.7 Comparison of nozzles on weight***

First 5 new 'good' nozzles were weighed as reference and t=0 point of the above figure (figure 6.7). Then 4 nozzles were replaced at the marathon salon, 2 after about 100 shave-wash cycles and 2 after approximately 600 cycles. The nozzles with 600 cycles were almost closed and the nozzles that passed through 100 cycles already showed some starting symptoms such as fading of the relief and impression marks of the SU. In the graph it can be seen that the weight of these nozzles (blue diamonds) is substantially higher than that of the 0-hour reference nozzles. Later, after respectively 33, 34, 49, and 65 cycles, the nozzles that replaced the 4 others were also weighed and added to above graph.

Then two other clusters were identified, both consisting of nozzles from appliances returned from the market. The first group consists of nozzles that failed at the customer (red crosses); the other group consists of at first sight good nozzles from appliances returned with another problem (pink squares). In order to be able to compare the shavers from the market with the ones from the marathon salon, the assumption was made that 1 day in use at the customer corresponds to 1 cycle in the marathon salon. Now it can be seen that the 'good' nozzles from the market did gain about as much weight as the nozzles from the marathon. After closer examination it was observed that the 'good' nozzles also started to show some of the visual symptoms listed above. But clearly, the failing nozzles returned by customers have become considerably heavier than the marathon salon nozzles and up to 27% heavier than a 0-hour nozzle. A possible way to explain this observation could be that at the customer the product is used by the same person in the same way over and over again, while at the marathon salon several different men use 6 different shavers, all in their own fashion (for example using different pre- and aftershaves or other cosmetics). Therefore the effect of a few extreme users in the marathon salon could be partially neutralized by others and this might explain why the market nozzles gain weight and stop up much faster. Another possible explanation is that due to the thorough disinfection process in the marathon salon a potential influencing stressor is neutralized in its ability to affect the nozzle.

Because weight increase can already be observed after a relatively small number of cycles in the marathon salon, it was decided to isolate the disinfection process and subject a number of new nozzles to this cleaning process (yellow triangles). This way it can be determined whether the Red X we are searching for is part of the cleaning process, thus the number of possible influencing stresses can be reduced substantially. Because none of these 5 nozzles gained any weight after 30, 60 or 120 cycles and none showed any of the visual abnormalities it can be assumed the Red X is not a part of the disinfection process.

Now it is observed that the failing nozzles are noticeably heavier, a cause for this increase in weight has to be found. The most obvious explanation is that the material of the nozzle absorbs or reacts with other material and so its physical/mechanical properties are altered and weight is gained. To determine if there are any differences in composition between new and failing nozzles, the advanced technology centre (ATC) was deployed.

The Advanced Technology Centre (ATC) is Philips DAP's central development laboratory. The ATC supports all DAP's lines of business by employing the latest technological insights to help create new products and manufacturing processes and solve production and market problems. The ATC has split its tasks into six main fields of research: materials, injection moulding, micro machining & metal forming, electronics, physics and analysis & applied physical chemistry. In this case we want to know if the chemical composition of the SEBS material of the failed nozzles differs from the chemical composition of that of recently produced new nozzles. Therefore the ATC section analysis & applied physical chemistry was enlisted to determine and explain possible distinctions. Potential deviations could indicate:

- the chemical composition of the material changed during customer use
- there have been variations in the quality of the supplied raw material
- process parameter adjustments in the injection moulding process influenced the material characteristics.

To analyse the composition of the 'soft-touch' material and to be able to compare different samples Fourier Transformed Infrared (FTIR) spectroscopy is used. FTIR spectroscopy is a cheaper and faster form of classical Infrared (IR) spectroscopy. IR spectroscopy is a type of absorption spectroscopy that uses the Infrared part of the electromagnetic spectrum. Infrared spectroscopy works because chemical bonds have specific vibration frequencies. The resonant frequencies can be in a first approach related to the length of the bond, and the mass of the atoms at either end of it. Thus, the frequency of the vibrations can be associated with a particular bond type. In order to measure a sample, a beam of monochromatic infrared light is passed through the sample, and the amount of energy absorbed is recorded. By repeating this operation across the range of interest, a chart can be built up [Wik05]. Samples with high levels of purity produce clear charts or spectra and can be looked up in a database/library. However in practice purity is rare and the spectrum is a mixture of different spectra therefore experience is required to identify the separate materials.

To be able to observe as much differences as possible and to draw well founded conclusions several samples were analysed, namely: a nozzle failed at the customer, a failed nozzle from the marathon, a new nozzle, a new Aquarius nozzle, granule (raw material for the nozzle) and a test sample for batch release. The analysis revealed one significant difference. The IR spectra of both the nozzle from the market and the nozzle from the marathon salon show a peak between approximately 1700 $cm^{-1}$ and 1800 $cm^{-1}$, which is not present in the spectra of the unused nozzle, the granule and the test sample for batch release. This difference can be observed in the following figure with at the top the spectrum of an affected nozzle and underneath the spectrum of a new nozzle.

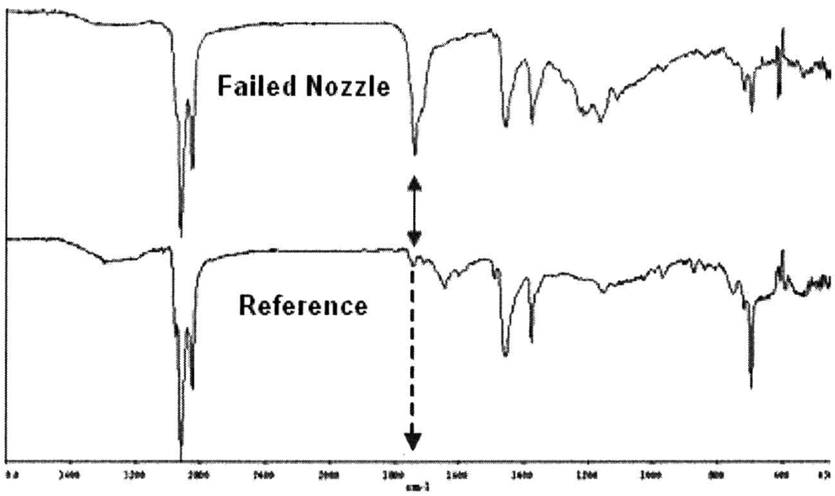



***Figure 6.8 IR Spectra***

Experience of ATC and chemical literature point out that peaks in the range between 1700 $cm^{-1}$ and 1800 $cm^{-1}$ are related to the presence of a double bond (=) between a carbon atom (C) and an oxygen atom (O). This C=O bond is present in a large number of chemicals among which: esters, aldehydes and ketones. The peak in the spectra can be caused by absorption of a different molecule that possesses a C=O bond but also by a chemical reaction taking place in the original material through which these C=O bonds are formed. To gain some more knowledge about the underlying conditions that lead to the change in IR spectrum some additional experiments were done:

- FTIR analysis on the moisturizing shaving lotion and gel (additive)
- 24h. immersion of granulated raw SEBS material in alcohol and additive followed by FTIR
- Thermal aging/degradation of SEBS granulated raw SEBS material followed by FTIR

An overview of the results is represented in the following table:

| Sample | As Ref. / C=O |
|---|---|
| ***Pluto*** | |
| New nozzle | Ref. |
| Market failure | C=O |
| Marathon nozzle | C=O |
| ***Aquarius*** | |
| Unused nozzle | Ref. |
| ***Granule*** | |
| Recent batch | Ref. |
| Recent batch immersed in additive (HQ170) | Ref. |
| Recent batch immersed in alcohol | Ref. |
| Recent batch after aging/degradation | C=O |
| ***Test sample batch release*** | |
| #1 | Ref. |
| ***Additive*** | |
| HQ170 | No C=O |
| HQ171 | No C=O |

***Figure 6.9 Paired comparisons by IR-spectra***

When these results are examined, it can be seen that the C=O bond only is present in the 'bad' nozzles and in aged/degraded SEBS. The aging of the material was done by ATC by means of alleged pyrolysis. In brief, pyrolysis is formally defined as chemical decomposition of organic materials by heating in the absence of oxygen [Wik05]. After the pyrolysis process an IR spectrum of the material was made, this shows a peak at 1700-1800 $cm^{-1}$ similar to what was found in the spectra of the 'bad' nozzles from customers and marathon salon. This outcome indicates that the failing of the nozzle could be the result of aging or degradation of the material; therefore a closer look was given to the material properties of SEBS and its degradation process in particular.

SEBS belongs to the group of styrene based thermoplastic elastomers (TPEs) and is a so-called block copolymer; two hard and rigid ending groups are chemically connected by a flexible and elastic central part. More information about these chemical concepts and the exact chemical structure of SEBS can be found in Appendix N. The manufacturer of the material (KRATON Polymers) states that degradation of elastomers is a result of polymer bond oxidation activated by mechanical stresses, high temperatures, ultraviolet radiation and chemical reactions. It can also be catalyzed by the presence of and contact with metals [Kra00]. This degradation process is schematically reflected in Appendix O. More scientific literature [All00, All02, All03] describes and emphasizes the role of thermal oxidation, ozone and photo-oxidation (UV irradiation) in the degradation process of SEBS. A striking result of the degradation processes described in these articles is the presence of a peak in the IR-spectra of the degraded material near to 1700-1800 $cm^{-1}$. These peaks are the outcome of a number of complex chemical reactions taking place in the SEBS material leading to an altered chemical structure and resulting in a deterioration of mechanical properties, melt flow characteristics and discoloration [Kra00]. All these properties seem to correspond to our observations of the failing nozzles and confirm the assumption that the outer-layer of SEBS material is subject to natural aging/degradation. However, the chemical reactions taking place in the SEBS during degradation eventually all lead to chain scission, which causes the SEBS to turn brittle, loose weight and shrink [Kra00]. This is conflicting with the SEBS on the nozzles, which became softer, increased weight and swelled. Therefore degradation of the SEBS on itself cannot be the root cause of the problems with the PLUTO nozzles.

### 6.3.3 Variables search

Now, with the knowledge material degradation by itself is not the failure mechanism present in the PLUTO nozzles, another possible explanation for the weight increase, visual alteration and change in IR-spectrum has to be found. Based on the preceding information, it seems reasonable to assume that the SEBS absorbs a certain substance as a result of which the weight of the nozzle increases and the material properties are modified, moreover this particular substance or the resulting product of its reaction with SEBS shows a peak in its IR-spectrum around 1700-1800 $cm^{-1}$. Another data point is that this substance should be present in the 'shaving phase' of the process at the marathon salon. This once more restricts the possible influencing stressors to a better manageable number. The suspected remaining stressors are:

- Additive (HQ170/171)
- Skin fat (sebum)
- Pre/Aftershaves
- Other cosmetics (perfume, skin care products, suntan lotion, etc.)

Because there are uncountable different pre- and aftershaves and other skin related cosmetics on the market with each a multiple of different ingredients, it is impracticable to isolate the specific ingredient ourselves. Therefore additional literature was consulted [RTP05, Ell04, Jul02] and this revealed that several chemical components indeed do affect the properties of SEBS. This can be easily observed from the charts in Appendix P. The most striking conclusions are:

- SEBS can swell up to hundreds of mass percents when immersed in oil
- SEBS is poorly resistant to/soluble in organic solvents, fuels, other hydrocarbons and gamma radiation

With regards to the differences observed during the paired comparisons study in the previous subparagraph, especially the first listed material characteristic seems relevant. Next to mineral oil, also fats, which become fluid at room temperatures, belong to this category. Because the failure is to a smaller extent present in almost all used PLUTO appliances it looks like skin fat (sebum) could cause the problem. For a quick determination whether skin fat is indeed the Red X, the failure mechanism has to be accelerated. According to figure 5.8 a phase 2 failure can be accelerated by means of increasing the level of the relevant stress or increasing the likelihood of occurrence of the relevant stress and practice this stress on pre-selected products. Because in paragraph 6.2 it was determined no relevant sub-populations of products are involved, therefore no pre-selection of products is needed. Now the stress on account of the skin fat (sebum) can be accelerated in two ways:

- **Increased probability of extreme stress:** during actual use by the customer or in the marathon salon the shaver is regularly cleaned and the skin fat is mostly removed. In this experiment the nozzle will not be cleaned so there is a continuous contact between SEBS and skin fat.
- **Increased level of extreme stress:** normally during shaving, the skin leaves behind a thin film of skin fat on the parts of the nozzle it touches. In this experiment the complete SEBS layer of the nozzle is rubbed in with a substantial amount of pure skin fat (sebum).

As we have to do with a failure mechanism that is dominated by chemical reactions there is another option for accelerating the failure mechanism. The speed of chemical reactions is described by the so-called Arrhenius equation [Luy00]. By elevating the temperature, it becomes possible to carry out tests requiring considerable less products and testing hours. Therefore in the experiment a temperature (80°C) well above the normal operating temperature was selected. To be able to disprove resistance of designers who think this temperature is unrealistically high and to reject the possibility that the additive has anything to do with the failure, also the two different additives were included in the test. Because there existed a risk the additives would curdle at elevated temperatures, these experiments started at lower temperatures and step-stressed (10 C) every 24 hours. Besides it is interesting what the influence of the mechanical force of the SU on the nozzle is on the failure. To determine if the failure mechanism did already set in, the sample nozzles were periodically weighed and visually inspected. The design of the tests and summarized results of the experiments are printed in Appendix Q + R.

These results point out that the failure can be rapidly reproduced by combining the stressors skin fat and an elevated temperature. To confirm skin fat is also the Red X causing the problems arising in the market and both additives do not, IR-spectra of a sample of skin fat and of both additives were made and compared with the spectra of failed nozzles in Appendix S. From these charts it can be noticed that the IR-spectrum of the skin fat sample shows a similar peak around 1700-1800 $cm^{-1}$ as present in the spectra of the market failures, whereas this peak is lacking in the spectra of the additives. Therefore it is supposed the failure mechanism as it arises in the market is identical to the failure mechanism that is identified, described and reproduced in this chapter.

## 6.4 Follow-up

It has been demonstrated that the concepts and techniques described in chapter 5 enable identification and reproduction of field failures in a fraction of the time. Identification of the root cause itself does not solve the problem and cannot the end point of the process. Continuation of the research may provide additional useful information to support prevention of the failure and its accompanying costs. For a future generation of PLUTO shavers, a design change may be considered and the information gathered must be stored in an unambiguous manner so the organisation is capable to learn from the past.

### 6.4.1 Experiments

A number of relatively simple additional experiments can considerably increase the knowledge of material and design and reduce inherent performance risks. Suggested starting points for further research could include:

- Execution of a FTIR-analysis on the failed sample from the experiment in subparagraph 6.3.3. Until now only the IR-spectrum of pure skin fat was compared with the IR-spectrum of a failed nozzle. Therefore only the correspondence in the peak around 1700-1800 $cm^{-1}$ could be observed. Full spectra analyses and comparison might reveal important additional information.

- In this chapter the failure was successfully reproduced with skin fat as the most important stressor. However the same failure mechanism, swelling of the SEBS material, in literature [El104] (Appendix P) also was observed in other fat or oil based products. In practice, next to skin fat the nozzle possibly makes contact with for example suntan cream or oil-based pre- or aftershaves. The effect of these products might be tested in the same way.

- Several designers believed the chosen temperature of 80°C was unrealistically high. Therefore the test can start at a lower temperature and be increased every time interval until any symptoms of the failure mechanism can be observed, in a similar way as done with the nozzles in the heated additive (Appendix M).

### 6.4.2 Design changes

When the anticipated future costs of the failure are higher than the costs of a possible design change the product should be adjusted. The anticipated future costs of the failure are composed of the costs of repairing failed products (costs of a repair (€) x number of repairs) augmented with the costs of dissatisfied customers switching over to a competitor the next time they buy a shaver. Based on the information from CaRIS and the information gathered in this chapter combined with sales and prospective sales figures an estimation of the number of future repairs can be made. The other part of the costs is a lot harder to assess as it requires detailed insight in customer behaviour.

The costs involved in a design change could consist of time of designers, new moulds, contracts with material suppliers, testing and release of the new design. Feasible solutions for the treated problem could be:

- Change the material of the nozzle. Choose another TPE to form the soft-touch outer layer of the nozzle. In Appendix P other TPEs can be found that are more resistant to swelling in oil and high temperatures, yet these materials are likely to be more expensive. Another option is to make the complete nozzle of one material, e.g. the cheaper hard polypropylene which is more resistant to chemicals and heat, but in that case the soft-touch layer will be lost which may result in decreased shaving comfort.

- Change the design of the nozzle. The design of the nozzle could be adjusted so that the inside of the opening of the nozzle, similar to AQUARIUS, is not covered with the SEBS material. In that case the nozzle will not close when the SEBS swells under the influence of skin fat or other oil-based products.

### 6.4.3 Failure Mechanism Database

Historical information on failures is interesting because it can help in avoiding failures in the future, the same failures should not be made twice. Therefore an unambiguous orderly procedure for storing this useful information is important. Available information on field problems is captured in two areas:

- Customer complaints that enter the organization via a National Sales Organization (NSO) or the in-house Drachten service centre. When a customer complaint enters the organization it should be forwarded to the department that is most likely able to find the root cause of the problem. Here it will be analysed further in a similar way as has been done in this chapter. Thus, of all incoming customer complaints a detailed analysis should be available, including the failure mechanism behind the failure and actions (technical change proposals) that have been taken to prevent the problem in the future.

- Information from CaRIS, the online repair information system that is connected to a number of service organizations. CaRIS provides information on the service activities that are executed in the service organizations. In this database, among other data, information on component failures and the replaced components is given. For analyzing risks, this information is immediately useful and applicable. For example Pareto's of component failures per shaver type can be made.

These two information sources have to be combined to develop a complete failure mechanism database. The steps needed to fill in the database of failure mechanisms could be as follows:

1. Collect all customer complaints and their failure mechanisms analysed over the last years. Categorise these complaints in failure mechanisms influenced by one or more stress factors.
2. Check the Pareto's of the different models over the last years to see to what extend these failure mechanisms and their related components can explain the components that are repaired in the field.
3. For the components that have a high repair rate but did not fail as a result of one of the failure mechanisms found by analyzing customer complaints, analyse what failure mechanism has caused this failure and add it to the failure mechanism database

| Failure Mechanism and Effect | Condition/Stress that caused failure in the field/test | Affected Module / Functional Block | Shaver Type | Sub-population/ All products | FCR | Design Change (TCP nr.) |
|---|---|---|---|---|---|---|
| By absorption of an oily/greasy substance the soft-touch SEBS layer that covers the nozzle swells up, through which the transit of additive to the shaving surface fails | Skin fat combined with an elevated temperature. | SU, and part of the additive application chain | **PLUTO (MU):**<br>- HQ7740<br>- HQ7760<br>- HQ7780 | All products | ±0,08% | .... |
| ........ | .......... | ........ | ...... | ......... | ..... | ..... |

***Figure 6.10 Failure Mechanism Database***

### 6.4.4 Input for Proactive Reliability Control

Then the information from both the failure mechanism database and the considerations made during technical change management should form the input for proactive reliability control. At the moment a new shaving system is under development that intends to use the same SEBS material to form a ring around the shaving heads to catch hairs. However, the failure mechanism identified in the PLUTO shaver might form a risk for the reliability of this new shaver. Now this potential risk can be rejected or confirmed by executing an analysis test on a specially prepared prototype. Or in this stage of the PCP another material can be picked with the same soft-touch as SEBS but with better resistance to skin fat and other stressors that it might encounter during all phases of its lifecycle.

## 6.5 Conclusions

In this chapter it has been shown how field failures can be analyzed and how the underlying failure mechanism can be identified and reproduced, making use of the concepts described in chapter 5. The failure that was examined is apparently the result of inadequate material selection for a particular part of the shaver. This means that the failure is not the result of a weaker sub-population of products, but potentially is present in all shavers on the market with this particular design. The fact that certain customers already do suffer from this problem and others do not, seems to be the result of both variation between users (amount of skin fat) and variation in use (cleaning frequency, time/place of use). Until now only the extreme customers returned failed products, by all appearances the majority of the customers will not encounter the problem inside of the warranty period but substantially later, nevertheless this will lead to dissatisfied customers and potential commercial consequences.

### 6.5.1 Current tests

During the product release of the Pluto-range the shavers were extensively tested. Two tests in particular were performed on the material of the pump slide:

**GTSS 7.1.4: Rubbing Test on rubber double shot products**
In this test the wear and tear of rubber double shot products was tested. A sample of the material is fixed to the testing equipment after which the test starts and the sample is moved automatically over a piece of sandpaper for a specified distance. After the test the sample is evaluated on the basis of decrease in volume, which should be less then a fixed requirement.

**GTSS 7.1.9: Swelling Test for rubbers**
The goal of this test is to determine the ability of rubbers to swell when they are immersed in lotions. Pieces of the rubber are measured and weighed before they are immersed in alcohol and different lotions for 24 hours. After the test the samples are measured again and judged on increase of volume against a fixed target.

In both of these tests the product satisfied the requirements. Also in other tests such as climatic tests and constant heat tests no abnormalities were found. The revealed failure was not observed during the current test programme because skin fat as the most important stressor causing the failure mechanism was overlooked and not used during testing. On top of that the requirements for the tests mentioned above were formulated for use of the SEBS material for grip panels on the cover of the housing. Therefore, without a reference to its application, exposure, etc. it is impossible to define standard specifications regarding reliability for this material; it is used in a different way in different designs and moreover used in a different way by the thousands of different consumers using the product. This finding can be generalized for other reliability related tests and therefore the following requirements can be added to the demands for a failure-oriented analysis test:

- *Tests are developed exclusively for a certain design: the design is exposed to all conditions that induce a risk for failing of that design in the market.*
- *Also relatively small design changes can effect the reliability of a (sub-)design, therefore the influence of a particular design change should always be taken into consideration*

### 6.5.2 Root-cause analysis in the PCP

The schematic representation in the figure below, clarifies the use of feedback information flows in support of root-cause analysis.

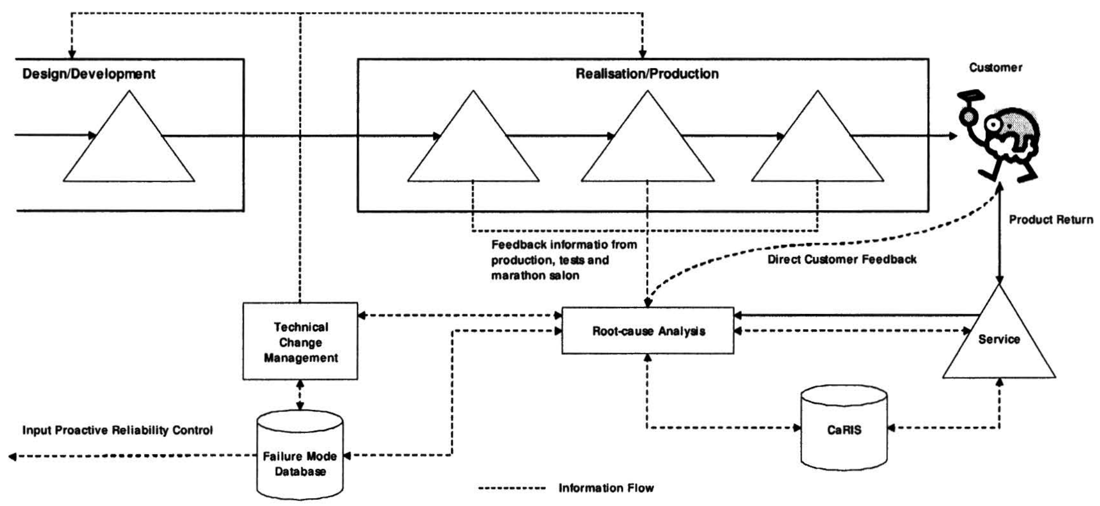



***Figure 6.11 Feedback Information Flows***

Information originating from production, tests, marathon salon, CaRIS and of course service where the returned products enter the organisation should be gathered. When an assumption exists that the failure is the result of unanticipated customer use the concerned consumers can be directly contacted. Then when the root-cause of the failure has been determined this should be communicated with service and fitted in the CaRIS. But more importantly it has to be decided whether the current design should be changed and the information should flow back to the right place in the organisation and the results of the root-cause analysis should be unambiguously recorded.

# 7 Proactive Reliability Control: Analysis Testing

## 7.1 Introduction

In the previous chapter a closer look was given to reactive reliability control. A failure arising on the market was analyzed, the failure mechanism was identified and reproduced in a test. However, it is always better to find all potential problems in a product before it is released for production or introduced in the market. Therefore this chapter recommends a different approach. A working method on proactive reliability control in the PCP of Philips DAP is proposed, using failure-oriented and DOE analysis testing. It will be described how tests should be designed and conducted to ensure that designs and products are reliable and durable in service.

It is assumed that the basic functionality has been achieved and demonstrated in the different steps of the Target Specification and Verification Program (TSVP); that is, at least one unit has been demonstrated to perform as specified and designed, and probably also for the anticipated lifetime. What has not been assured, however, is that all units to be produced will work over the whole range of specified conditions and expected lifetimes, or at least they will do so to a sufficiently high level of reliability.

Functional testing is basically deterministic: the item passes or fails the test and based on statistics it can be determined when there is done enough testing. However, testing for reliability and durability is fundamentally different. The reasons are that it is never known what the 'uncertainty gap' is between the theoretical and real capabilities of the design and the products made to it, for the whole population, over their operating lives and range of environments. In chapter 5 the uncertainties of strength and stresses were discussed and it was also noted that these uncertainties could be even further magnified by the effects of variations in use, users and products. The effects of these uncertainties can seldom be evaluated with confidence by any of the design analysis methods available. Therefore the central question of this chapter is how a test program can be set up that is able to find all weak points in a design and thus assure reliability whilst taking into account constraints like cost and time. In particular the different steps needed for setting up such a test will be discussed, including product selection, test timing and a risk analysis method. First, the method used to come to a well-structured strategy will be described.

## 7.2 Strategy and Requirements

As seen in chapter 2 and 6 the capability of an organisation to analyse and control problems can be expressed in the five different levels of the Maturity Index on Reliability (MIR) (Figure 2.8). Ranging from an uncontrolled process (Level 0) to a continuously improving learning organisation (Level 4). Proactive reliability control can be described exactly the other way round. It starts with a new or improved design, subsequently it should be predicted what the possible failure mechanisms are for this new or changed design. Then based on the outcome of the analysis tests, the potential effect of these failure mechanisms on sub-system behaviour should be predicted, eventually leading to an estimation of the product behaviour on the market. When this outcome is insufficiently the design needs to be changed and tested again. This is schematically reflected in the following illustration (figure 7.1).

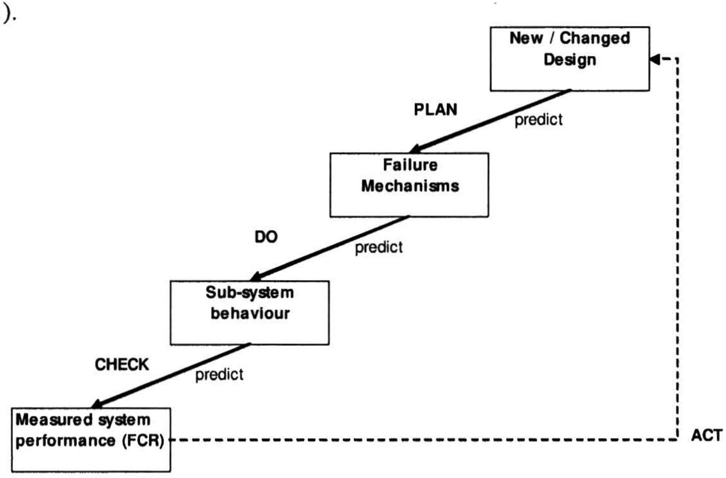



***Figure 7.1 Reverse MIR, proactive reliability control***

To ensure a continuous learning process and to come to a structured working method for the different test activities, Deming's Plan-Do-Check-Act (PDCA) cycle is used. This is a well-known model for continuous quality improvement consisting of a logical succession of four repeating steps that should be passed to come from a problem-faced to a problem-solved situation. This PDCA-cycle is illustrated in figure 7.2.

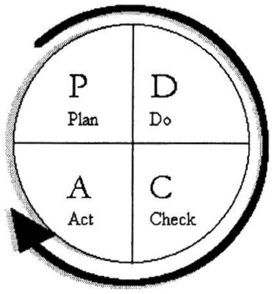



***Figure 7.2 The PDCA-cycle***

Following definitions for Plan, Do, Check and Act have been used for this research:

- **Plan:** Preparation of the test
- **Do:** Execution of the test and collection of data
- **Check:** Assessment of the test results, is design improvement necessary?
- **Act:** If necessary, make design improvements.

The content of these separate steps will be discussed in more detail in the following sections. Every correctly designed test method needs to comply with two general requirements: a test method should be both *repeatable* and *reproducible*. An analysis can be considered repeatable if it is possible to do the analysis in exactly the same way. This can be expressed as the variability in the measurements obtained by one person measuring the same item repeatedly. Reproducibility on the other hand implies that an analysis can be executed multiple times leading to the same results. If a test is not reproducible the results of the analysis may be due to coincidence. Reproducibility is the variability of the measurement system caused by differences in operator behaviour.

## 7.3 Plan

During the Plan-phase of the PDCA-cycle all required preparations for the execution of the test are made. All designs and design processes are different therefore a careful design specific preparation of the tests is necessary in order to get the right information from the tests and thus find all weak links in a design. The plan phase should at least include:

1. Product identification and test timing;
2. Making a risk analysis to identify all possible failure modes and causes for a design, resulting in the identification of the most important stressors and variables;
3. Translation of stressors into extreme environment test conditions simulating market situation as good as possible;
4. Develop test plan/procedure and prepare test equipment.

### *7.3.1 Product selection and test timing*

Analysis tests can be executed throughout the entire design process on different parts (components, functional modules or complete shavers) of the design. Next to the difference in test timing also the purpose of an analysis can vary; either it is aimed at finding potential design flaws or it is expected to determine whether a new design is better than the current. In a chronological order this comes down to:

- Testing of new components, functional modules or sub-assemblies in the early phases of the PCP. A general rule is that the quality and reliability of a (sub)design cannot be predicted from historical data if it differs more than 25 percent from earlier designs [Rah91]. During these tests all design flaws and weaknesses in the sub-design should be identified after which the sub-design can be improved and optimised. By doing so changes are made in the most favourable period of the PCP and following tests on the complete shaver can focus on the interaction effects with other sub-designs.

- Testing the first design of a new family of shavers of which no historical reliability information or earlier design experience is available. There is no information on interaction risks in this specific design.

- When a design is changed compared to previous designs and the influence of these changes is unknown. Tests have to reveal something on the effect of these changes on the reliability of the shaver. In this case the focus should be on the specific risks for these changes in the part and on interaction risks with other parts of the product.

Because testing all parts of the shaver would be too much time-consuming and even superfluous, next to above chronological order of different analysis tests, it is required to rank the different parts of the shaver in order of importance. To set up such a ranking from the start of a new design process, the design has to be split up into sub-designs. Different designs of one product, like the design of a shaver, are often to a very large extent comparable. Thus it is possible to make a general division of a product into sub-designs. This division could be based on the parts list such as is displayed in Appendix C. It can be necessary to adjust this general division for a specific product, but this division is the starting point for the ranking.

Then the next step is analysing per sub-design in what model this design approach has been used before; in exactly the same configuration or in a different one? For the same market segment with the same use(r) characteristics or for a different one? With the same manufacturing methods or different ones. Then, indicate whether the used sub-design is indeed the same, modified or actually completely new. Next information can be gathered from CaRIS on the FCR of the similar designs already in the market preferably in the same market segment. Resulting in a table as shown in figure 7.3.

| No. | Name of part or sub-design and component description if applicable | Similar Structure in prod. | Same | Changed | New | Old FCR |
|---|---|---|---|---|---|---|
| | | | | | | |
| | | | | | | |

***Figure 7.3 Sub-design analysis***

The collected information from this table can be used to rank the different sub-designs regarding risk and uncertainty. Uncertainty is defined as: the operational absence of information (useful experience and/or knowledge) from the past [Lui03]. This uncertainty depends upon the immaturity of a particular part or sub-design. Uncertainty can be expressed on the basis of the categories *'same'*, *'changed'* and *'new'* used in figure 7.3 above. Risk is defined as: the combination of a likelihood, severity and controllability of a certain risk event. Risk event is defined as "the combination of factors that trigger a loss" [Lui03]. To estimate the risk, the FCR of comparable sub-designs in the market can be observed and subsumed in different categories for the FCR; low, medium, high/unknown. Then this information of the different sub-designs can be represented in a scheme as the following:

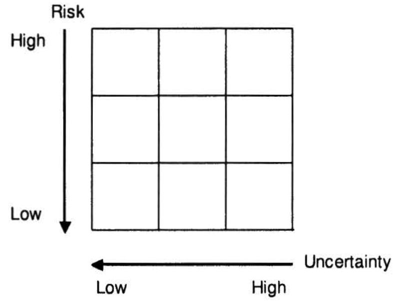



***Figure 7.4 Risk vs. uncertainty***

Traditional methods, like FMEA, focus on reducing the risk without considering the uncertainty involved in the prediction. However, the reliability problem is not effectively solved until all uncertainties are identified and reduced. There could have been uncertainties that lead to new or more serious risks or a higher probability of occurrence. The analysis test focuses on reducing the uncertainties so risks can be valued more accurately. Then the different sub-designs shift from right to left in above scheme, subsequently the design can be optimised to reduce the risk.

### 7.3.2 Risk Analysis

As discussed in chapter 2, failure oriented analysis tests are executed to confirm or reject risks that may or may not happen in a future product. This asks for a risk analysis in order to have all potential failure modes identified, before analysis tests are put into practice. This risk analysis has to identify all risky conditions that exist in the market for a specific design. Then during analysis testing the identified conditions should be translated into test conditions; as a result uncertainties are reduced and the prospective risks can either be confirmed or rejected, after which the risk analysis should be updated.

In order to prevent confusion, it is convenient to consider three aspects of failure [Oco01]. The underlying causes (physical, chemical, human) are the *failure mechanisms*. The *failure modes* are the immediate effects within a product or system, such as swelling or open circuit, etc. The *failure effects* are the effects as observed by product or system behaviour, such as loss of output, etc.

The demands for a good risk analysis for this purpose are:

- The risk analysis has to identify all potential failure modes the design can encounter during its lifetime on the market.
- For each potential failure mode, all factors that could contribute to it have to be described. These variables then can be simulated in tests and thus the risks can be evaluated.
- It has to be possible to set up the risk analysis at the start of the design process to enable tests as early as possible in the PCP.
- Updating of the risk analysis needs to be an integral part of the design process. When more information on a specific (sub)design becomes available, it will become possible to define reliability risks and causes in more detail and more specifically. Then also testing can become more specific.

The method to analyse the different sub-designs, described in the previous subsection, ensures that the entire design is evaluated and no parts are overlooked. Subsequently, all possible failures that the different sub-designs of the product could suffer from during their lives should be identified. The danger, as seen in the previous chapter, is to overlook certain failure modes in particular in new or changed sub-designs. To reduce this danger as much as possible there are several information sources that should be used to come to a complete record of potential failure modes for each sub-design.

#### Information Sources

- **A database of General Failure Mechanisms for Shavers.** This database and the way it should be set up were already described in the last part of the previous chapter. In this database, information is collected on conditions and phenomena that cause shavers to fail in the field. This information follows from reactive reliability control in the form of root cause analyses on customer complaints. The reason for setting up this database is the fact that only a few stress factors and failure mechanisms are causing a large part of the customer complaints and repairs. These failure modes repeat in consecutive generations of shavers and need a lot of attention to prevent the problems in the future. In this way this database contributes to a closed learning cycle. However the information is only useful for sub-designs that are identical or changed compared to earlier designs and not for sub-designs that are completely new or changed more than 25%.

- **The function structure.** In the new Target Specification and Verification Program (TSVP) critical functions have to be proven as from the start of the PCP. Next to proving this functionality it is also necessary to prove the reliability of the various functions. It is important to know that the shaver is able to function as it was meant to function, but at the same time it is just as essential to prove that it will function this way for its entire lifetime. Therefore per sub-design all functions have to be defined that have to be performed by this part of the shaver. A function describes the input, output and condition quantities of a (sub)system without any reference to solutions. A function can be described by means of a verb, e.g. *leading additive from the cartridge to the shaving surface.* Subsequently several failure effects and failure modes can be found that prevent the (sub)design from performing this function. To get a complete overview of the functions it may be helpful to follow the product from its creation to the end of its life and figure out which functions it might need at each stage of that period.

- **The rollercoaster curve.** In each phase of the life of a shaver it has to do with different sorts of failures leading to customer complaints. An extensive explanation of the concept of the rollercoaster curve and the failures to expect in the different phases of the curve can be found in section 3.1. Now it is possible to walk through the life of a (sub)design and indicate for each phase the potential failure modes (risks) and underlying failure mechanisms.

- **An overview of general failure mechanisms.** The presence of certain materials and constructions in combination with specific conditions (stresses) lead to a standard collection of failure mechanisms. For example metal or plastic components that are subjected to combined continuous or cyclic stress and high temperature will gradually increase in length, this symptom is called creep. An incomplete table of these failure mechanisms can be found in Appendix T.

To determine all relevant stresses Ishikawa diagrams can be used [Bij01]. They are also called fishbone or cause and effect diagrams. Ishikawa diagrams help in structuring cause and effects of a problem. The technique starts with the definition of a failure mode or problem (effect). Then, once the effect is defined, the factors that may contribute to its cause are pointed out. These are the possible reasons that the problem exists. While there may be only one actual cause to a problem, there are many potential causes that could appear. Subsequently these main causes can be split up in sub-causes etc. resulting in a figure in the form of a fishbone. A generic example of an Ishikawa diagram is shown in figure 7.5.

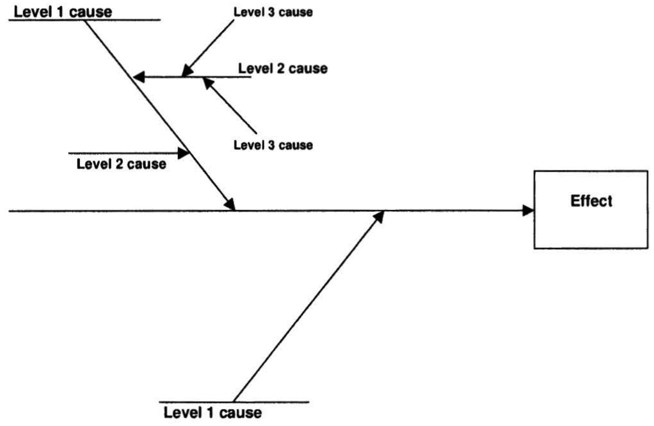



***Figure 7.5 A generic Ishikawa diagram***

The steps that are recommended for constructing an Ishikawa diagram are:

1. Identify and clearly define the outcome or effect to be analysed. This can be a high level problem e.g. failing of the product, but also a lower level sub-problem can be investigated further e.g. failing of a certain function;
2. Draw the spine and create the effect box;
3. Identify the major factors that contribute to the effect being studied; In case of product reliability problems these major factors will be the principal stress categories e.g. electrical stress, mechanical stress, environmental stress, etc.
4. For each major branch, brainstorm sub-causes that may be the cause of the effect.
5. Identify increasingly more detailed levels of causes and organize them under related causes. Asking a series of why/how questions can help doing this.
6. Verify the causes by gathering data to see if it has significant impact on the problem. This verification is done during the analysis tests.

### 7.3.3 Test Conditions

The definition of test conditions is based on the stress factors, the causes of the risks that are indicated for the design in the risk analysis. After the most important stresses and variables for a design have been identified by setting up the Ishikawa diagram, these stresses should be translated into test conditions, simulating as good as possible the market situation. The DQD can propose concept test conditions for the most important stresses, next these conditions should be discussed with the responsible designers.

### 7.3.4 Test Procedure

After the test conditions have been defined, a test procedure can be defined for the AST. The stress factors are combined up to levels that exceed the maximum design specification levels to smoke out the weak links in the reliability of the design. The test goes beyond the design specification limits and thus can find design errors that are below the surface of the design specifications and can find the margin that the design has. For every test individually it has to be decided which stress levels to increase and how to increase them. The selection of stresses to be applied, singly or in combination, should be based upon experience and on the (sub)design being tested, and not on specifications or standards. The conditions that can be applied during testing can be split up in several groups:

- ***Conditions that are constant in the test.*** Only one level is worst case for the setting of controls: the maximum level. Therefore this condition should remain constant.
- ***A condition that is 'worst' at different levels.*** For example the mains tension can be most harmful at its lowest and its highest level.
- ***A condition that depends on the received signal.*** For example on/off power switching.
- ***A condition that is used to increase the stress on the design.*** For example, like in the experiment in chapter 6 the ambient temperature can be used to increase the stress, while temperature influences and accelerates the particular failure mode.

Another aspect of the test that should be determined in this stage is the sample size. The aim of analysis tests is to find weak links in the design that can be improved or to compare design solutions and not to analyse test results statistically. We need other than statistical considerations to determine the number of prototypes to be tested. Therefore as many items as can be practically made available, within project cost, time and other constraints should be subjected to a failure-oriented test. As discussed above, there is no 'ideal' quantity from a statistical point of view. However, by testing more than one item the chances of discovering design weaknesses are increased and testing one item is far more beneficial than testing not at all. In the case of establishing the effectiveness of a design change and to ensure that no new failure modes have been introduced 3 samples from each model are sufficient to perform a B vs. C analysis.

The project team (DQD, relevant designers) shall determine when a product is considered to have failed. Often this can be defined on the basis of automatically measuring a particular response parameter. But there are also situations in which the failure occurs but the response cannot be measured automatically. This is e.g. the case when the failure can only be observed visually. In such a situation there are two possible alternatives: rely on visual inspections or define some measurable indication to detect the response. Furthermore the project team shall determine when the test can be considered a success. This definition can be seen as a condition to check if the test is finished. A test run is finished either if the product has failed or the maximum test run duration has been reached.

## 7.4 Do

After the Plan-phase, when all preparations have been finished, the Do-phase can start. During this phase the developed test procedure is executed and relevant data is collected. To be able to execute a test, DQD needs to prepare the test. The test set up has to be made, equipment needs to be prepared, the test conditions have to be arranged and time of a test engineer has to be scheduled. When everything is prepared the test can be executed, following the test procedure as determined in the last part of the plan phase. During the test, data on failures should be collected. To make it possible for designers to analyse the failure, detailed information is needed on the exact conditions under which the product failed, which components failed, after how many hours, in only one set or in several ones, etc.

When a failure occurs there are several possibilities, the failure can be caused by a bad component but not be related to the design. It can be set specific, only arising in the tested set but not in others. The third possibility is that the problem is design related. In order to find out, the products that fail in the test should be repaired so that the test can continue. If the same failure does not repeat at all after the set is repaired, it is probable that the failure was caused by a bad component in the tested product. If the failure repeats in the repaired set, but not in other sets, the failure will presumably have been set specific. Only if the failure also repeats in other test samples, the conclusion can be drawn that a design specific failure has been found. It is clear that all failures need to be analysed. It is possible that a component related failure is the result of just that one bad component. But the probability that there are more bad components in this or other batches is certainly not negligible. And it should be checked if it is necessary to do an entrance control. This is similar in the case of a set specific failure. The reason why this set in particular is causing problems needs to be determined and it has to be made sure that the problem in this set does not become a general problem in all sets. When the conclusion is that the failure is design related, the only solution is a design change.

## 7.5 Check

### 7.5.1 Analyse the failure

Next, when the test is completed, the test results should be analysed. The analysis of failures in the test should be aimed at deciding on the actions that are necessary. Therefore the root cause of all failures in the test needs to be found. This root cause analysis should be initiated by the owner of this particular test from the DQD and should be handed over to the designer(s) or design group responsible for this particular (sub)design.

Then if the failure is material related or another specific purchased component has failed, the purchasing department has to be informed. Then it should be examined whether the bad component was incidental or that there are more components with the same characteristics among the purchased components and it forms a structural problem.

If the failure was a set specific failure it has to be examined whether only this set is weak or that there is a high chance that there will be other sets that show the same weaknesses.

### 7.5.2 Categorize the failure

The objective of failure analysis is to support the decision-making on the necessary follow-up actions. To assist this decision-making process, it is recommended to categorise the risks. Zapf et al [Zap92] state that such a taxonomy proves its relevance if different risk types lead to different practical consequences. In this case a categorisation has been made with three classes: high, medium and low risks. The failures should be categorised by those who execute the analysis of the failure, together with the Product Manager who has the final responsibility for the quality of the design. The following figure shows how such a categorization could look like:

| Risk Category | Characteristics |
|---|---|
| HIGH | A failure in the test could happen in the field just as it happened in the test. The reliability error in the design is detectable under conditions that are within the normal design specifications stress, although the failure might have occured under overstress conditions. For component and set specific failures, the chance is high that more components and more sets have the wrong characteristics for use in the field |
| MEDIUM | A failure in the test happened under overstress conditions and is not immediately expected to fail under normal stress levels. But there is a weak point in the design, the design is not robust and reliable on this point. Due to e.g. aging of the design, stress levels in the market exceeding specification stress levels, etc., the product can fail on the market. There is an actual chance that more components or sets have the same wrong characteristics |
| LOW | A failure in the test happened under overstress conditions and is not expected to fail under normal stress levels or in case of a component or set specific error, the chance that the failure will repeat in other sets and components is considered small. |

**Figure 7.6 Risk Classification**

## 7.6 Act

The action that is taken as a follow up of the test results depends on the outcome of the Check-phase and the new estimation of the FCR. Action can vary from asking the procurement department to investigate the quality of a certain component to making a design change or doing nothing. Another important decision that has to be made is when action needs to be taken. Is it necessary to immediately give a red light for continuation to the next design stage? This can be the case when serious problems come up which e.g. increase the estimated FCR dramatically. In less serious cases, it can be sufficient to know where the problem in the design is exists; during the following design stages extra attention should be given to strengthening those weak links. If intervention is necessary then in the act-phase the actual action, in the form of a design change, has to be taken. The criterion given by Zapf et al [Zap92] that different risk types need different practical consequences leads to the following risk action plan:

| Risk Category | Action |
|---|---|
| HIGH | The error in the design has to be improved immediately and, if possible, the improved design has to be evaluated in the same test as that the failure came up (at the same milestone). In the mean time, when designers make the design improvement, continue the test, searching for more weak links, by removing the condition that causes the repeated failure in the test or make other arrangements that make it possible to continue the test. |
| MEDIUM | The weak point in the design needs to be watched carefully and if it is possible to improve the design without great expenses, this has to be done immediately. For these kinds of risks, it is necessary to try and get a good insight in the consequences of leaving the weak point in the design. Further downstream the PCP the problem either has to be solved or the consequences of leaving the risk are exactly known and accepted. Continue the test as described above. |
| LOW | No immediate action has to be taken but the failure has to be documented and taken into account further down the PCP. Continue the test. |

***Figure 7.7 Risk Action Plan***

Then when a design change has been made, it has to be verified whether this change is sufficient to solve the problem. This has to go through a PDCA cycle again. Plan a follow-up test, in which the same conditions are applied that caused the problem earlier and search for the limits of the new design solution. After execution of the test it can be checked whether the design change is an improvement (B vs. C) and whether this improvement is satisfactory. Actions have to be taken if the solutions were not satisfactory, this can be repeated if necessary.

## 7.7 Testing for Variation

In any design in which performance, reliability or durability might be affected by variations, they must be included in the test programme. If only one or a few variations are considered likely to have significant effects, these effects are understood and there are no interactions between them, then conventional one-at-a-time tests, using the AST approach might be sufficient. However, if these assumptions cannot be safely made, then statistical experiments should be performed to determine which variations and interactions are significant.

Statistical experiments and the analysis of the results provide information on *how much* the variables and interactions affect parameters of interest. They do not provide explanations *why*. Only theoretical knowledge of the underlying science can provide such answers. However, the statistical information can be valuable in generating clues for better understanding and control.

Statistical experiments and AST are complementary approaches in development testing. The table (figure 7.8) below gives some guidance on which approach to select for particular situations. Note that these are by no means clear-cut criteria and there will often be shades of grey between them. The decision on the most appropriate method or combination of methods should be made in relation to all of the factors: risks knowledge, costs and time.

| | DoE/AST? |
|---|---|
| Parameters: electrical, dimensions, etc. | DoE |
| Effects on measured performance parameters, yields | DoE |
| Stress: temperature, vibration, etc. | AST |
| Effects on reliability/durability | AST |
| Several uncertain variables | DoE |
| Not enough items available for DoE | AST |
| Not enough time available for DoE | AST |

***Figure 7.8 DoE/AST selection [Oco01]***

The close and natural linkage between AST and DOE appears from the following possible applications [Bho00]:

- **Solving Elusive Problems**
If a problem is elusive, such as never being found during tests and only discovered in the field, a combination of DOE and AST can be a successful approach, as observed in the case study from chapter 6. The objective is to take units in production and subject them to one or more combined stress tests, until failures similar to what the customer experiences occur. Now the time-to-failure or the stress-to failure becomes the response or output or Green Y and one of the DOE-tools can be employed to determine which input variables cause the problem.

- **Evaluating the Effectiveness of Engineering Changes**
Here, B versus C can be employed to evaluate each engineering change. B stands for a better design; C for the current design. It calls for testing three B's and three C's (done in a random order sequence) and then ranking the outputs from best to worst. If the three B's outrank the three C's in output, with no overlap, it can be claimed with 95 percent confidence that the B design is better than the C design. These very small sample sizes are adequate when the output (Green Y) is a variable. But if it is an attribute, is expressed in high yield percentages, or has a very low defect rate, a sample of three B's and three C's is too small and does not have sufficient discriminative power to detect the difference between B and C. This is where the combination of a DOE tool (B versus C) with AST comes in. The object is to convert an attribute into a variable by subjecting both B's and C's to progressively higher and higher stress levels using AST. Then, the time to failure or the stress-to-failure becomes a variable, making a sample of three B's and C's sufficient [Bho00].

- **Cost Reduction**
The primary purpose of combining AST and DOE is reliability improvement. However, these techniques can also help to maintain product reliability when reducing product cost. First a cost reduction target should be established. Next a list of all high-cost parts or modules has to be made. Then the items on this list should be prioritized, balancing the degree of cost reduction potential against the danger of reliability reduction, tooling, supplier risks and cost of experimentation. Subsequently an alternate approach to provide the required function of the item should be found. Then this alternate approach can be subjected to the same tests as the former approach and can be evaluated.

## 7.8 Analysis Testing in the PCP

In this last section a schematic overview of the analysis test as described in the preceding of this chapter and its position in the PCP are given.

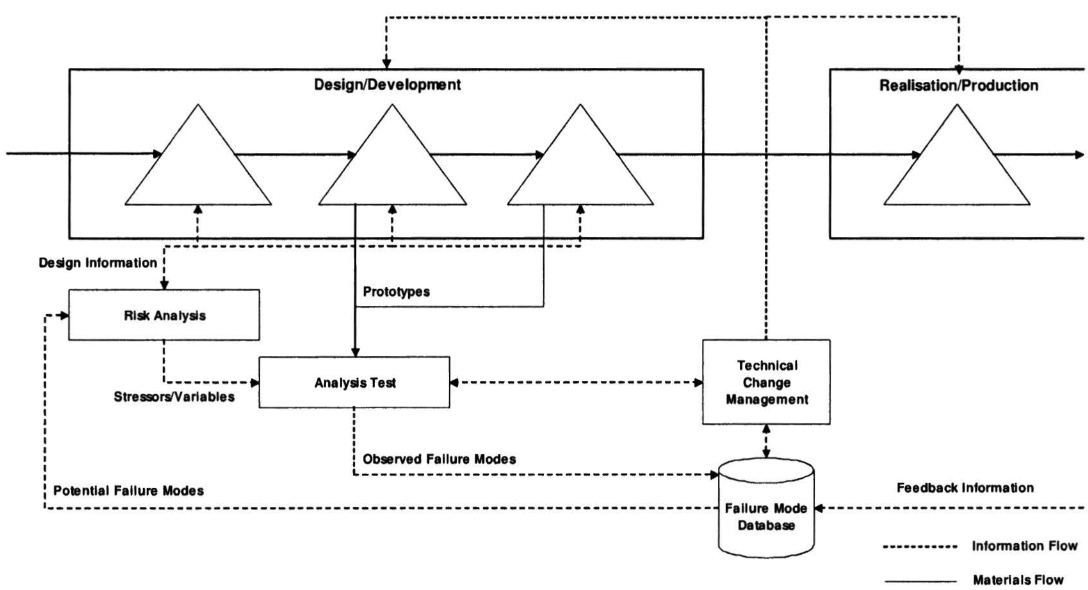



***Figure 7.9 Analysis Testing in the PCP***

# 8 Conclusions and Recommendations

This final chapter discusses the conclusions and recommendations of this research project. First the conclusions that can be drawn from the research will be discussed in section 8.1. Then this report will be concluded with recommendations for further research in section 8.2.

## 8.1 Conclusions

The product creation process (PCP) of high-volume consumer products is currently changing. These changes are the results of four major trends: a decreasing time-to-market, increasing product complexity, globalisation and segmentation of business processes, and a changing role of the customer. Every individual customer expects ever-increasing product functionality and excellent product quality and reliability. Simultaneously the time available to cope with these requirements is decreasing due to the increasing innovation speed. As a result, it becomes more and more important to predict product quality and reliability related problems already in the early phases of the PCP. This, naturally, influences the two principal activities of the Development Quality Department (DQD) where this research has been executed. These activities are: 1) collecting, analysing and classifying feedback data from the field and from mass-production, and 2) testing activities to assure product quality and reliability. A literature review on the changing requirements for the business process in chapter 2, and an analysis of the actual situation at Philips DAP in chapter 3 led to the following conclusions:

- Philips DAP has a considerable strength having a Service Centre (SC) at the Drachten plant. This way failed shavers can be examined by the responsible development department to find the root-cause of the problem and establish a solution for the specific problem. However it occurs that solutions are designed before the exact technical and/or organisational root-cause of the failure is known. The failure can not be replicated in a test environment, besides no sub-populations of extreme products/users are identified. This may form a serious threat in the form of repeating of similar failures in future generations of shavers. Another weakness of the feedback information flow is the metric used to quantitatively express the performance of the shavers at the customer, the Field Call Rate (FCR). This is a very slow metric due to the use of moving annual totals and is useless for close monitoring of the field behaviour of products; it is fundamentally incompatible as a figure of merit for class 1 and 2 failures. Additionally, analysis of the speed of the feedback flow of a particular High-End (HE) shaver (section 3.4.3) pointed out there exists a very long time interval between the moment of production and the moment of purchase, only 40% of the shavers were sold within 6 months after production date. This suggests a very large number of shavers in the pipeline between plant and customer. Therefore it gets more and more important (cheaper, faster, better for reputation) to find product flaws and weaknesses yourself during product testing.

- Philips DAP uses an extensive test program that is based on more than 65 years of experience in producing electric shaving appliances. However due to the increasing innovation speed these existing tests do not longer satisfy for all products. Products that make use of new technologies (product, production) and/or are developed for an unfamiliar market result in new product-users interactions that bring about uncertainties. These uncertainties can eventuate in reliability risks. To control the reliability of these kinds of products information is needed from the start of the design process, to reduce uncertainties. Early in the design process necessary design changes are easier to carry through and less costly. Thus potential quality or reliability problems should be detected as early as possible. The current tests only start when the PCP is about halfway through. Besides, to optimise product reliability, the test has to indicate all potential imperfections and weaknesses in a design and thus can steer improvement actions. Most of the current tests are so-called validation tests that aim at proving the product meets specifications, and therefore not suitable for reliability optimisation.

The conclusion can be drawn that Philips DAP has a rigid PCP that fits with a rather static market. This way of working satisfies if products are developed using mature building blocks and technologies for a mature market, which is the case for most shavers in the low- and medium-end segments. However, to stay competitive and retain the market leadership, Philips DAP has to constantly innovate. New technologies are used, new markets are entered and even new accessories such as a washing machine for the shavers have to be developed, in less time with increasing customer demands regarding product quality and reliability. In these cases merely validation tests at the end of the PCP (figure 2.9) do not longer satisfy and there is a need for analysis tests in the early phases of the PCP aimed at product optimisation (figure 2.10). It is a challenge how to do such an analysis test. Therefore the second part of this thesis was aimed at answering this question.

- First the root-cause of a reliability failure that came up on the market, and which was not found during the current test program, was examined. This analysis showed that a combination of Design of Experiments (DoE) and Physics of Failure (PoF) based Accelerated Stress Testing (AST) was able to identify the relevant stresses and variables. And subsequently the failure mechanism as it arose at the customer could be reproduced in a fraction of the time. This root-cause information should be communicated to the relevant stakeholders in the PCP, so they can take adequate measures. Then this information and the follow-up actions should be recorded and made available to all relevant stakeholders to prevent reoccurrence of similar problems. At the same time this should form the input for feedforward reliability control activities. The root-cause analysis resulted in two additional requirements for the failure-oriented analysis test:

    - *Tests are developed exclusively for a certain design: the design is exposed to all conditions that induce a risk for failing of that design in the market.*

    - *Also relatively small design changes can affect the reliability of a (sub-)design, therefore the influence of a particular design change should always be taken into consideration.*

- Then in the final chapter a way of working was proposed for the execution of analysis tests in the early phases of the PCP, aimed at product optimisation.

In the following figure both the feedback control loop through root-cause analysis and failure reproduction, and the feedforward control loop through analysis testing are schematically depicted:

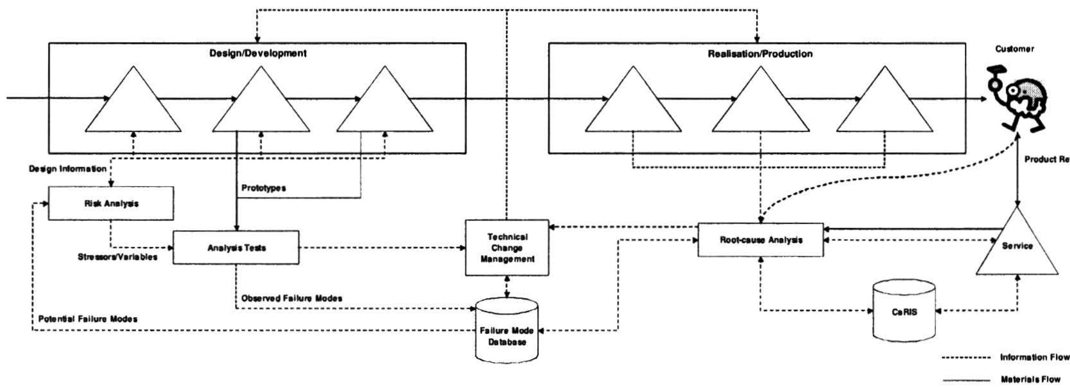



***Figure 8.1 Feedforward and Feedback Control Loops in the PCP***

## 8.2 Recommendations

Working with universities, trained professionals and outside consultants is a shortcut to learning, but true learning and true understanding comes only with practising a lot. Reading this paper is a head start but only the beginning. This section discusses a number of recommendations for future research based on the findings from this research.

- ***Gain experience with the proposed risk analysis and analysis tests on specially prepared prototypes.***

In Chapter 5 it was demonstrated that Physics of Failure based Accelerated Stress Testing was able to reproduce a failure that turned up at the market within a fraction of the time. However, the tested model was a final design and the relevant stresses were determined from feedback information. In feedforward analysis tests, specially prepared prototypes of components or (sub-)designs should be tested earlier in the design process to find as much flaws and weaknesses as possible.

- ***Evaluate the consequences of analysis testing on the validation/verification release tests.***

When in an early stage of the PCP analysis tests have been executed this influences the verification/validation tests in later phases of the PCP. The goal is to improve the product by identifying weaknesses and flaws as early as possible in the design process as well as to determine the critical stressors that contribute to the product failure. These identified stressors can also be used to update or improve the existing verification and validation tests to release future generations of shavers that make use of the same sub-design. In the future when failure-oriented analysis testing has been successfully applied and has proven to be able to significantly improve the products by eliminating their weaknesses, it is possible that analysis tests can even replace part of these tests.

- ***Testing can and should be fun.***

When a worker spends at least half of his waking hours on the job, the work should be fun. This author believes from his experiences at Philips DAP that testing can be and should be fun. This is not only the responsibility of management but also the responsibility of the worker her/himself. Both parties work on a flexible and effective work environment. At Philips DAP the employees of the Development Quality Department enjoyed lots of freedom, but when there was much work the workers did not mind to work longer. There are always periods that are less interesting and an employee could get bored. The DQD is responsible for the performance, quality and reliability for new developed products. If the responsibility of the DQD is kept in mind an employee knows where this less interesting time is useful for.

# References


All00] Allen, N.S., Edge, M., Wilkinson, A., Liauw, C.M., Mourelatou, D., Barrio, J., Martinez-Zaporta, M.A. (2000); *"Degradation and stabilisation of styrene-ethylene-butylene-styrene (SEBS) block copolymer"*; Polymer Degradation and Stability 71, p. 113-122

[All02] Allen, N.S., Edge, M., Wilkinson, A., Liauw, C.M., Mourelatou, D., Barrio, J., Parellada, M.D., Ruiz Santa Quiteria, V. (2002); *"Influence of ozone on styrene-ethylene-butylene-styrene (SEBS) copolymer"*; Polymer Degradation and Stability 79, p. 297-307

[All03] Allen, N.S., Luengo, C., Edge, M., Wilkinson, A., Barrio, J., Parellada, M.D., Ruiz Santa Quiteria, V. (2003); *"Photooxidation of styrene-ethylene-butylene-styrene (SEBS) block copolymer"*; Journal of Photochemistry and Photobiology A: Chemistry 162, p. 41-51

[Bas03] Baskoro, G., Rouvroye, J.L., Bacher, W., Brombacher, A.C. (2003); "Developing MESA: An Accelerated Reliability Test"; 2003 Proceedings Annual Reliability and Maintainability Symposium, p. 303-308

[BdO00] Brombacher, A.C., Ouden, E., den (2000); Presentation *"Testing in time driven PCPs"*, Eindhoven University of Technology

[Ber00] Berden, T.P.J., Brombacher, A.C., Sander, P.C. (2000); *"The building bricks of product quality: an overview of some basic concepts and principles"*; International Journal of Production Economics 67 3-15

[Bho91] Bothe, K.R. (1991); "*World Class Quality: using DOE to make it happen"; AMACOM*

[Bho00] Bhote, K.R. (2000); "*World Class Quality: using DOE to make it happen"; AMACOM*

[Bro92] Brombacher, A.C., Geest, D.C.L. van, Herrmann, O.E. (1992); *"Simulation, a tool for designing-in reliability"*; ESREF'92 conference Schwabisch's Gmünd (D)

[Bro00] Brombacher, A.C. (2000); *"Designing Reliable Products in a Cost and Tie Driven Market: a conflict or a challenge"*; Intreerede 18-02-'00 Eindhoven University of Technology

[Bro04] Brombacher, A.C., Sander, P.C., Sonnemans, P.J.M., Rouvroye, J.L. (2004); *"Managing product reliability in business processes 'under pressure' "*; Reliability Engineering and System Safety 88, p. 137-146

[Bus90] *"Cost of non-quality"*; Business Week, April 30, 1990

[For96] Forsberg, K., Mooz, H. (1996); *"Visualizing Project Management"*; John Wiley & Sons INC.

[Gan05] Ganesh, N., Lu, Y., Ouden, E. den, Brombacher, A.C.(2005); *"Managing Quality & Reliability with Less Information"*; Proceedings - Annual Reliability and Maintainability Symposium, p. 379-384

[Gra01] Graef, de, M.R. (2001); *"Betrouwbaarheid van technische systemen: anticiperen op trends"*; Stichting toekomstbeeld der techniek, Den Haag

[Kra00] *"Aging Characteristics of Kraton G compounds"*; KRATON Polymers ™ (2000)

[Lew96] Lewis, E.E. (1996); *"Introduction to reliability engineering"*; John Wiley & Sons

[Luy99] Lu, Y., Loh, H.T., Ibrahim, Y., Sander, P.C., Brombacher, A.C. (1999); *"Reliability in a time-driven product development process"*; Quality and Reliability Engineering International 15, p. 427-430

[Luy00] Lu, Y., Loh, H.T., Brombacher, A.C., Ouden, E. den (2000); *"Accelerated stress testing in a time-driven product development process"*; International Journal of Production Economics 67, p.17-26

[Luy02] Lu, Y. (2002); *"Analysing Reliability Problems in Concurrent Fast Product Development"*; PhD thesis, Eindhoven University of Technology

[Min99] Minderhoud, S. (1999); *"Quality and Reliability in Product Creation – Extending the Traditional Approach"*; Quality and Reliability Engineering International 15, p. 417-425

[Oco01] O'Connor, P.D.T. (2001); *"Test Engineering – A concise guide to cost-effective design, development and manufacture"*; John Wiley & Sons

[Pet99] Petkova, V.T., Sander, P.C., Brombacher, A.C. (1999); *"The role of the service centre in improvement processes"*; Quality and Reliability Engineering International 15, p. 431-437

[Pet00] Petkova, V.T., Sander, P.C., Brombacher, A.C. (2000); *"The use of quality metrics in service centres"*; International Journal of Production Economics 67, p.27-36

[Pet03] Petkova, V.T. (2003); *"An analysis of field feedback in consumer electronics industry"*; PhD thesis, Eindhoven University of Technology

[Qre04] "*Research Program department of Quality and Reliability Engineering, Eindhoven University of Technology"*; http://w3.tm.tue.nl/en/capaciteitsgroepen/qre/research/

[Rah91] Raheja, D.G. (1991); *"Assurance Technologies, Principles and Practices"*; McGraw-Hill, NewYork

[San99] Sander, P.C., Brombacher, A.C. (1999); *"MIR: The use of reliability information flows as a maturity index for quality management"*; Quality and Reliability Engineering International 15, p. 439-447

[San00] Sander, P.C., Brombacher, A.C. (2000); *"Analysis of quality information flows in the product creation process of high-volume consumer products"*; International Journal of Production Economics 67, p. 37-52

[Smi91] Smith, P.G., Reinertsen, D.G. (1991); *"Developing Products in Half the Time"*; Van Nostrand Reinhold, New York

[Smi98] Smith, P.G., Reinertsen, D.G. (1998); *"Developing Products in Half the Time: new rules, new tools"*; Van Nostrand Reinhold, New York

[Ulr00] Ulrich, K.T., Eppinger, S.D. (2000); *"Product Design and Development";* Irwin McGraw-Hill, New York

[The95] Theije, S.M., de (1995); *"Design and Reliability: reliability control through reliability tests in the design process of monitors";* Technische Universiteit Eindhoven

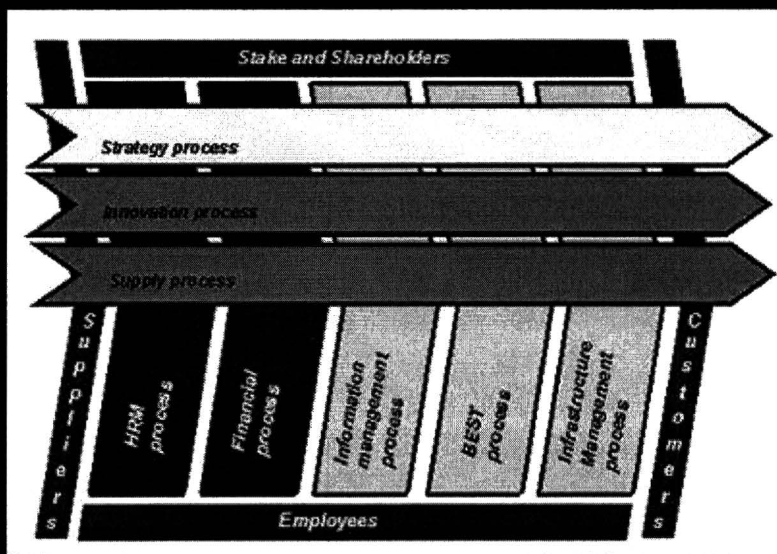
[Whe92] Wheelwright, S.C., Clark, K.B. (1992); *"Revolutionizing product development Quantum leaps in speed, efficiency and quality"*; Free Press, New York

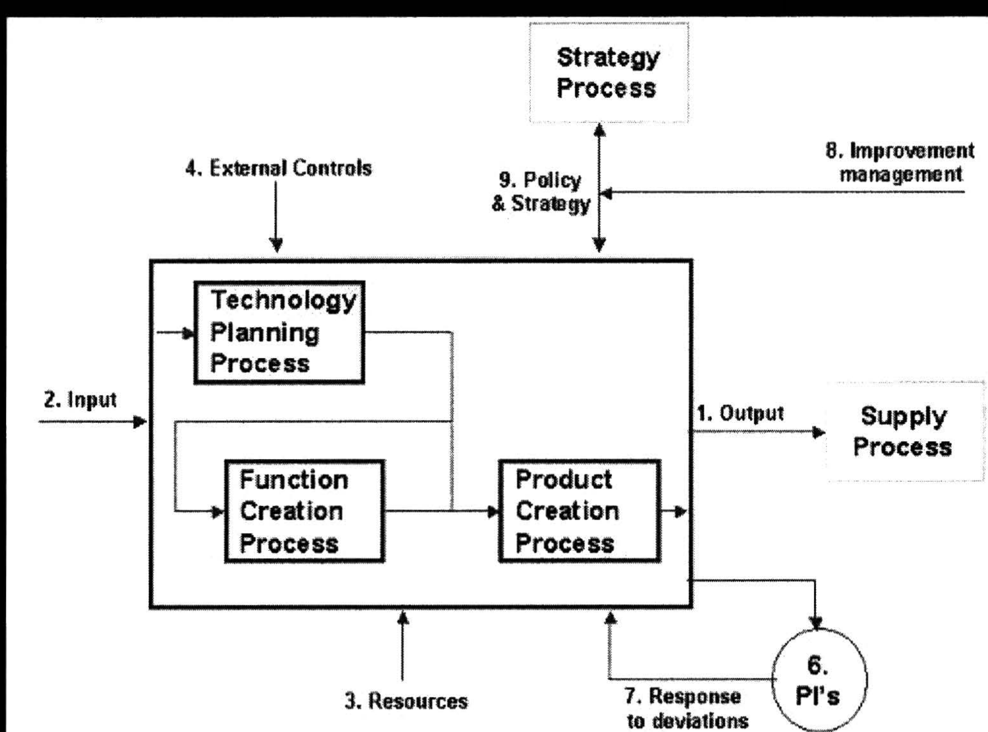
[Won88] Wong, K.L. (1988); *"Off the bathtub onto the roller-coaster curve"*; Proceedings annual reliability and maintainability symposium, IEEE, New York

[Zap92] Zapf, D., Brodbeck, F.C., Frese, M., Peters, H. and Prümper (1992); *"Error Taxonomy"*; International Journal of Human-Computer Interaction 4

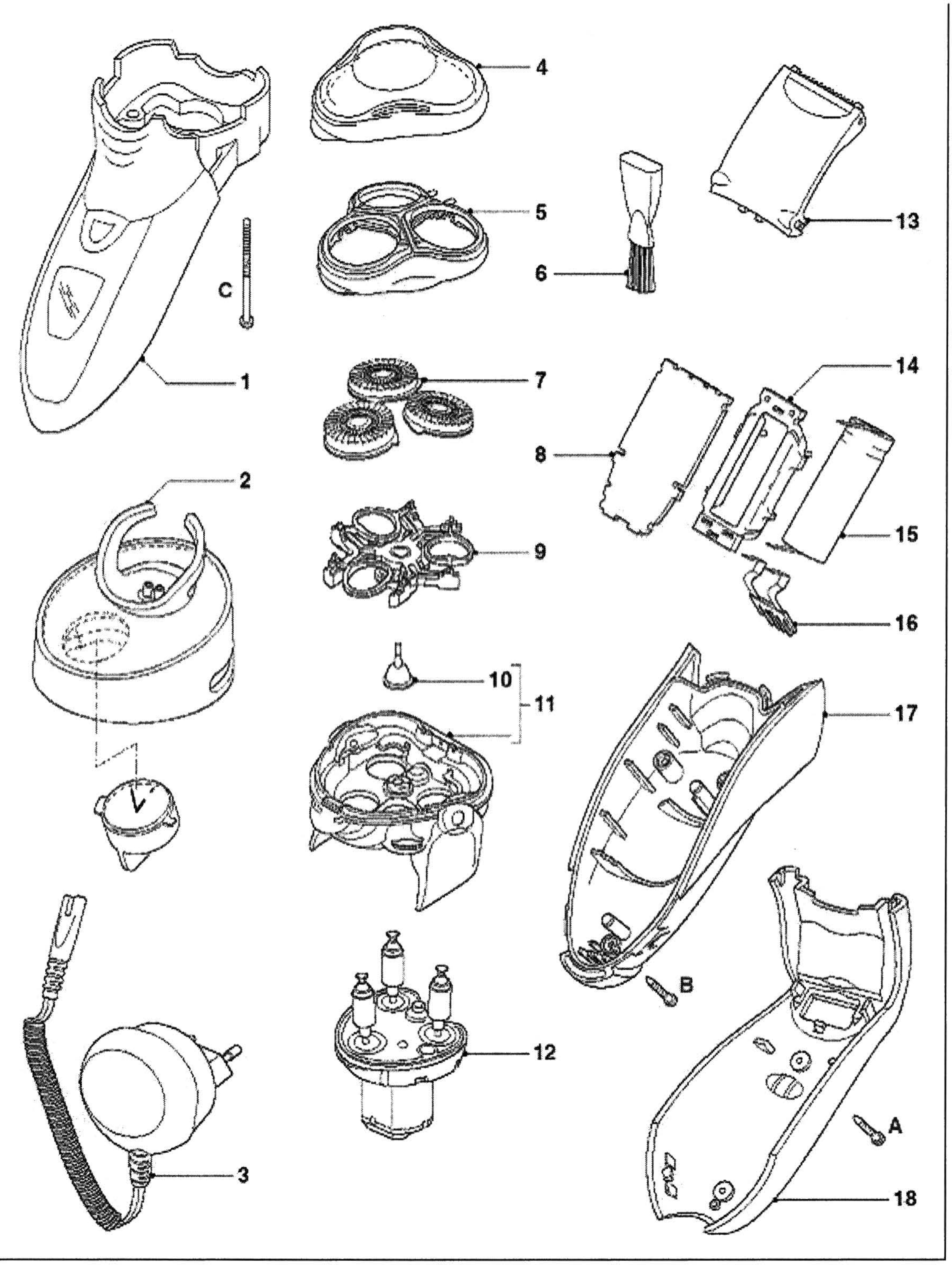
# Appendices

# Appendix A – Processes



# Appendix B – Exploded View

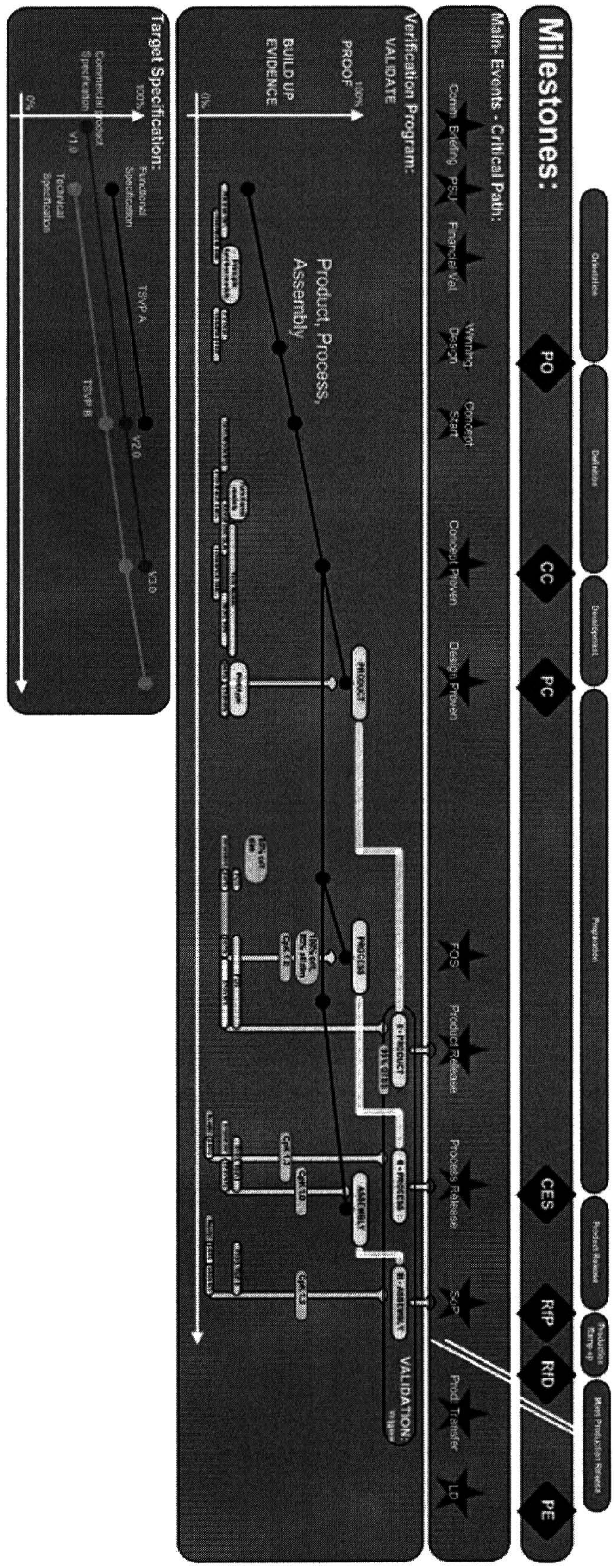


# Appendix C – Parts List

| Pos | Service code | Description |
|---|---|---|
| 1 | 4222 036 11370 | Housing shell assy |
| 2 | 4222 036 11030 | Stand |
| 3 | 4222 036 04080 | Power plug EUR |
| | 4222 036 04090 | Power plug GBR |
| | 4222 036 05110 | Power plug Can/Tw/Ven |
| 4 | 4222 036 11100 | Protection cap Quasar |
| 5 | 4222 036 11110 | Bracket assy |
| 6 | 4222 036 02770 | Brush |
| 7 | 4222 036 11150 | Shaving head 9-series |
| 8 | 4222 036 11180 | Power supply |
| 9 | 4222 036 11220 | Holder assy |
| 10 | 4222 036 11230 | Contour following pin |

| Pos | Service code | Description |
|---|---|---|
| 11 | 4222 036 11210 | Sidegrip assy |
| 12 | 4222 036 11250 | Driving unit 3,6 V |
| 13 | 4222 036 11270 | Trimmer assy |
| 14 | 4222 036 11280 | Spacer Li-ion A |
| 15 | 4222 036 11290 | Li-ion battery |
| 16 | 4222 036 11300 | Inlet connector BB |
| 17 | 4222 036 11320 | Cover assy |
| 18 | 4222 036 11140 | Cover shell |
| A | 4822 502 14545 | Screw |
| B | 4222 036 11480 | Screw (BBM) |
| C | 4222 036 11490 | Screw |
| | 4222 036 11560 | Pouch |
| | 4222 036 11590 | Pouch |
| | 4222 036 11530 | Cassette |
| | 4222 036 10860 | Clock |

# Appendix D – The PCP + TS&VP



# Appendix E – FCR Prognosis

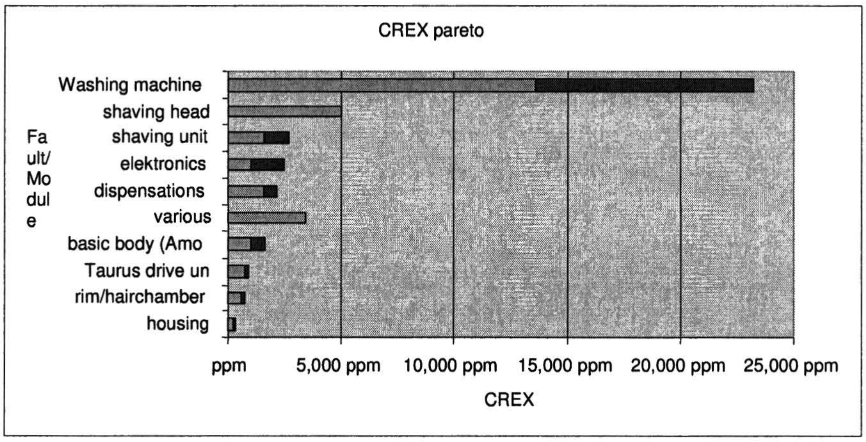
**CREX Corona light**

| Corona Type | sales in K | best estimate for failure rate in % | N failures best estimate failure rate in K | with a high level of confidence the failure rate is below in % | N Failures with high conf below in K | information |
|---|---|---|---|---|---|---|
| Corona light | 1600 | 2.93 | 46.88 | 3.92 | 62.72 | Incl washing machine |
| Total calls in K: | | | 46.88 | | 62.72 | |
| Costs in K (Euro 27 per call) | | | 1265.76 | | 1693.44 | |

mei 3, 2005

| Weigted FCR Corona light: | 2.93% | 3.92% |
|---|---|---|

| nr. | Elements that contribute to Failure Rate | FMEA reference number | Reference Values: Chosen reference (part/process/test/expert) | Reference Values: Failure rate of reference (ppm) | Estimated Failure Rate: Deviation from reference | Estimated Failure Rate: Correction factor | Certainty | Results: Estimated failure rate (ppm) | Results: CREX (ppm) |
|---|---|---|---|---|---|---|---|---|---|
| 11 | Washing machine | 0 | CREX sheet travassi | 13,600 ppm | new design | 1.0 | 100% | 13,600 ppm | 23,200 ppm |
| 2 | shaving head | 0 | Jupiter MAT0563 | 5,000 ppm | Sensotec shaving system | 1.0 | 100% | 5,000 ppm | 5,000 ppm |
| 1 | shaving unit | 0 | Indiana MAT563 | 2,000 ppm | new design | 0.8 | 60% | 1,600 ppm | 2,667 ppm |
| 7 | elektronics | 0 | Indiana MAT05062 | 1,000 ppm | | 1.0 | 40% | 1,000 ppm | 2,500 ppm |
| 14 | dispensations | 0 | CREX sheet dispensations Corona | 1,600 ppm | | 1.0 | 100% | 1,600 ppm | 2,180 ppm |
| 10 | various | 0 | CREX sheet various corona | 3,440 ppm | | 1.0 | 100% | 3,440 ppm | 2,030 ppm |
| 3 | basic body (Amon) housing | 0 | new | 1,000 ppm | new design | 1.0 | 60% | 1,000 ppm | 1,667 ppm |
| 13 | Taurus drive unit | 0 | CREX sheet Taurus | 750 ppm | | 1.0 | 100% | 750 ppm | 950 ppm |
| 6 | rim/hairchamber | 0 | Jupiter MAT470 /new | 600 ppm | | 1.0 | 80% | 600 ppm | 750 ppm |
| 4 | housing | 0 | luna MAT470 | 200 ppm | shells | 1.0 | 60% | 200 ppm | 333 ppm |
| 5 | trimmer | 0 | new / Indiana | 200 ppm | pop up trimmer | 0.8 | 60% | 160 ppm | 267 ppm |
| 8 | battery | 0 | Indiana MAT05062 | 200 ppm | NiMh | 1.0 | 100% | 200 ppm | 200 ppm |
| 9 | power plug | 0 | Indiana HQ7815 MAT0563 | 100 ppm | H4 | 1.0 | 100% | 100 ppm | 100 ppm |
| 12 | Recharging stand Scuba | 0 | na | ppm | | 1.0 | 100% | ppm | ppm |



# Appendix F – FMEA-sheet and Maturity Grid

| Failure Mode And Effect Analysis | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Onderwerp: | | | | Datum: | | | | |
| No | Part / proces | Potentieel probleem | Oorzaak | Gevolg | Gewichts factor | Evolutie factor | oplossing | Verantwoor-delijke | Timing | Klassificatie |
| 1 | | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | | | | | | | | | |
| 4 | | | | | | | | | | |
| 5 | | | | | | | | | | |
| 6 | | | | | | | | | | |
| 7 | | | | | | | | | | |
| 8 | | | | | | | | | | |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| 11 | | | | | | | | | | |
| 12 | | | | | | | | | | |

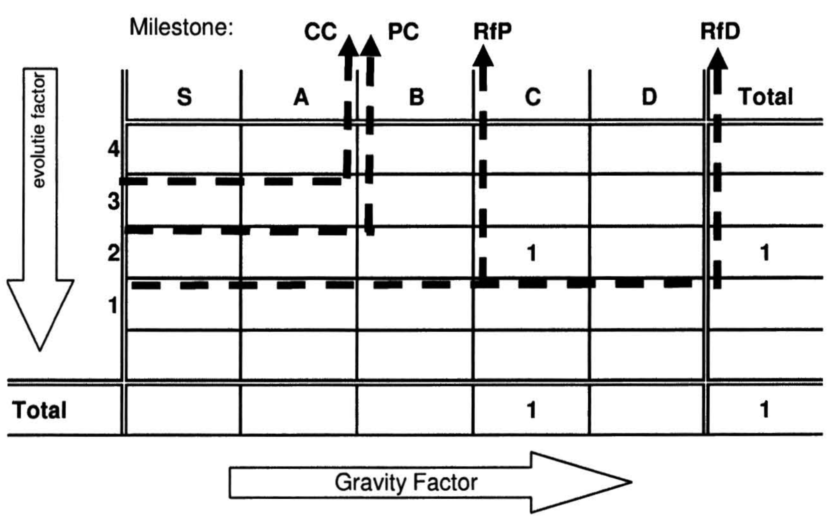
**Gravity factor** S = Non-conformity with safety standards or requirements

A = Results in a not producible / unsaleble product
B = Results in a product, which can be produced with big problems or not be accepted by a critical customer
C = Results in a product, which can be produced or sold with minor difficulties
D = Problem accepted by the customer and the management

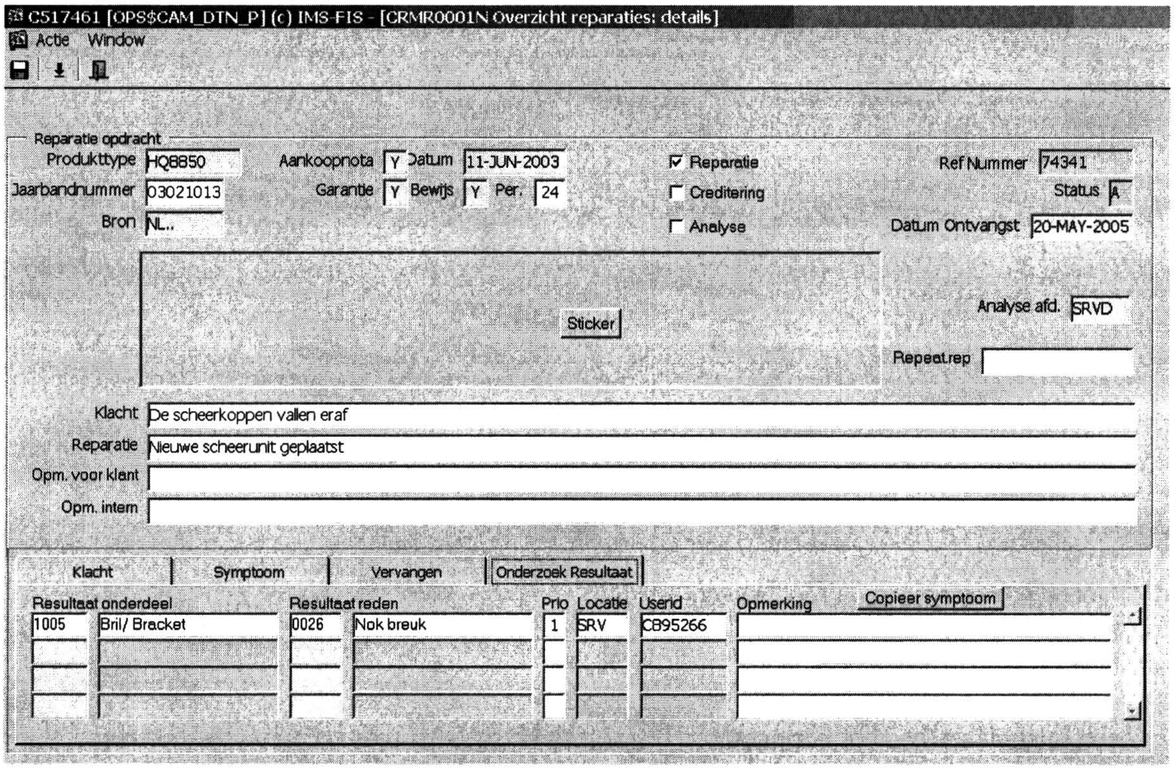
**Evolution factor** 4 = Cause unknown

3 = Cause known, solution unknown
2 = Solution known, but not evaluated yet
1 = Evaluation of solution is positive, but not implemented yet
0 = Solution is implemented

Project: Module:



# Appendix G – Repair sheet service centre



# Appendix H – DoE-Tools overview

| *Tool* | *Objective* | *Where Applicable* | *When Applicable* | *Sample Size* |
|---|---|---|---|---|
| Multi-Vari Chart | • Reduces a large no. of unrelated, unmanageable causes to a family of smaller and related causes, such as time-to-time, part-to-part, within part, machine-to-machine, test position-to-test position, etc.<br>• Detects nonrandom trends | • Determines how a product/process is running, a quick snapshot, without massive, historical data that are of very limited usefulness<br>• Replaces process capability studies<br>• In some white-collar applications | At engineering pilot run, production pilot run, or in production | Min. 9–15 or until 80% of historic variation is captured |
| Components Search | From hundreds or thousands of components/subassemblies, homes in on the Red *X*, capturing the magnitude of all important main effects and interaction effects | Where there are 2 differently performing assemblies (labeled "good" and "bad") with interchange-able components | At prototype, engineering pilot run, production pilot run, production, or field | 2 |
| Paired Comparisons | Provides clues to the Red *X* by determining a repetitive difference between pairs of differently performing products | Where there are matched sets of differently performing products (labeled "good" and "bad") that cannot be disassembled | Same as components search | 5 to 8 pairs of "good" and "bad" product |
| Variables Search | 1. Pinpoints Red *X*, Pink *X*, etc.<br>2. Captures the magnitude of all important main effects and interaction effects<br>3. Opens up tolerances of all unimportant variables to reduce cost | • Where there are 5 to 20 variables to investigate<br>• Excellent problem-prevention tool | • Excellent in R&D, development engineering, and in production for product/process characterization<br>• Also pinpointing Red *X* after multi-vari or paired comparisons | 1 to 20 |
| Full Factorials | Same as variables search | • Practical only where there are 2 to 4 variables | Same as variables search | 1 to 16 |
| *B* vs. *C* | • Validates superiority of a new or better (*B*) product process over a current (*C*) one with a desired statistical confidence (usually 95%)<br>• Evaluates engineering changes<br>• Reduces cost | • Follows one or more of the above 5 tools<br>• When problem is easy to solve, *B* vs. *C* can bypass above tools<br>• In some white-collar applications | • In prototype, pilot run, or production | Usually 3 *B*s and 3 *C*s |
| Realistic Tolerance Parallelogram (scatter plots) | • Determines optimum values (levels) for Red *X*, Pink *X* variables and their maximum allowable tolerances | • Following above 6 tools | • In pilot run of product/process | 30 |

# Appendix I – Pluto pictures I

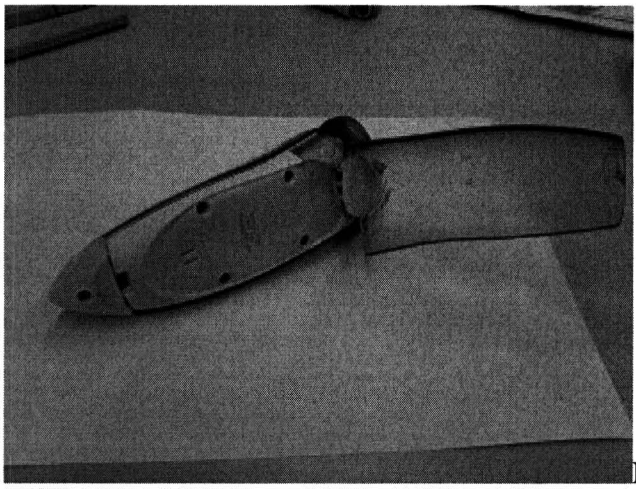


Photo1

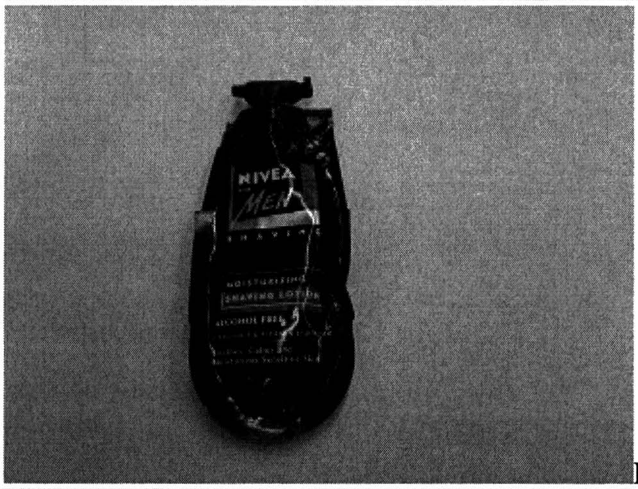


Photo2

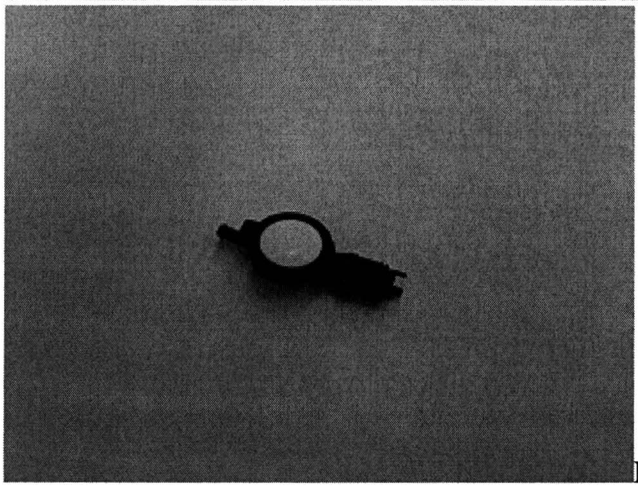


Photo3

# Appendix J – Pluto pictures II

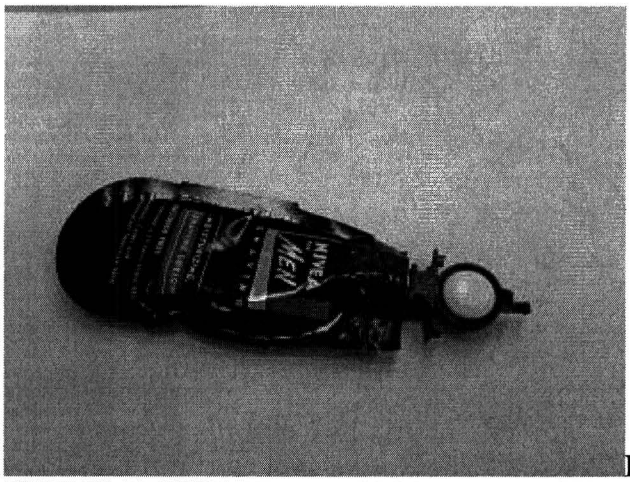


Photo4

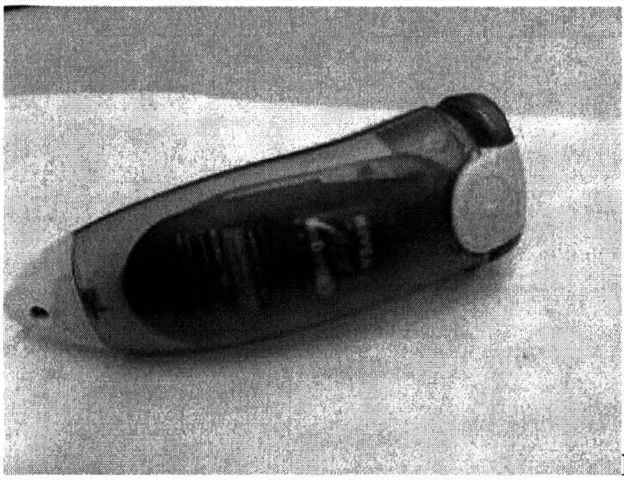
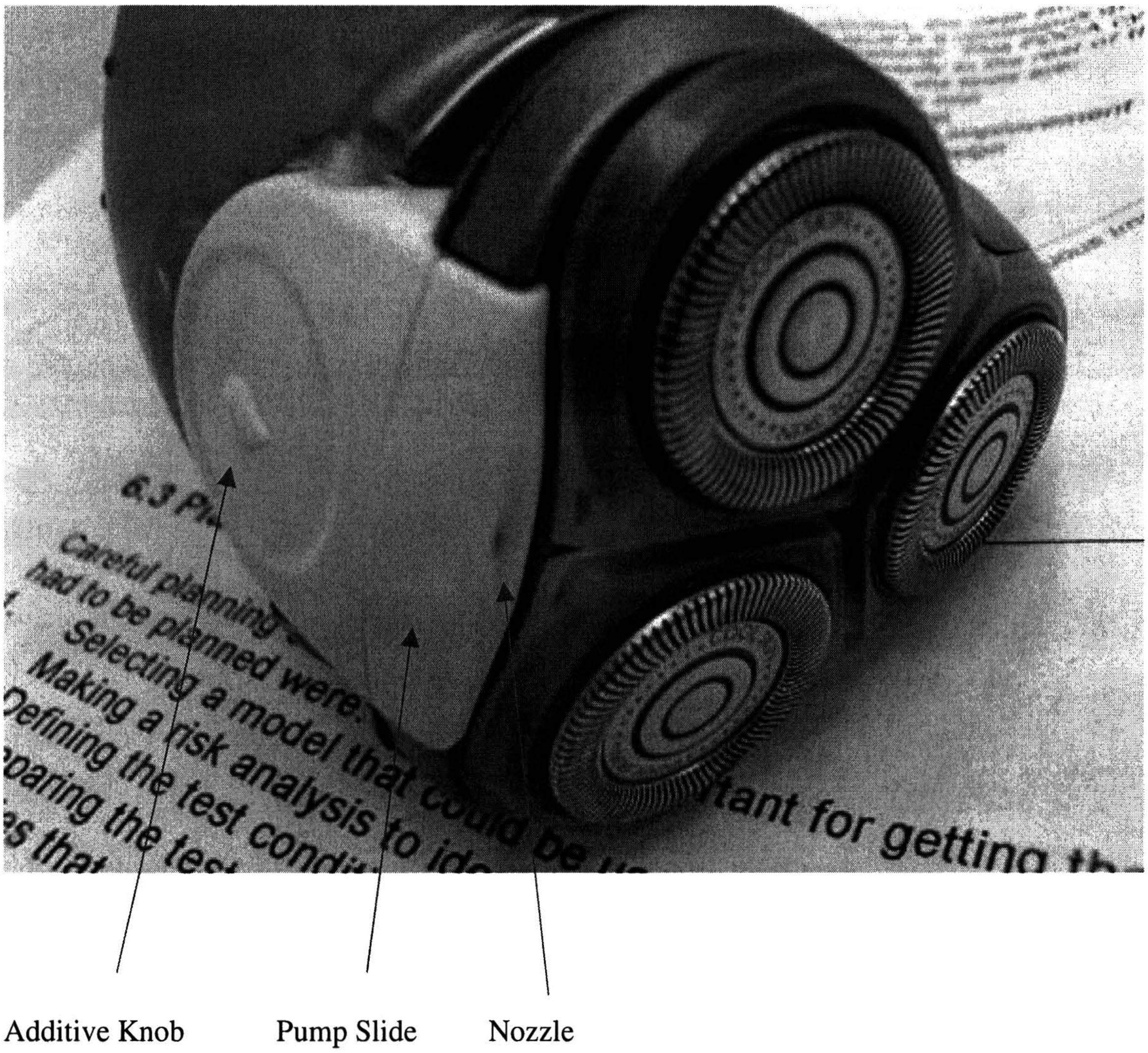


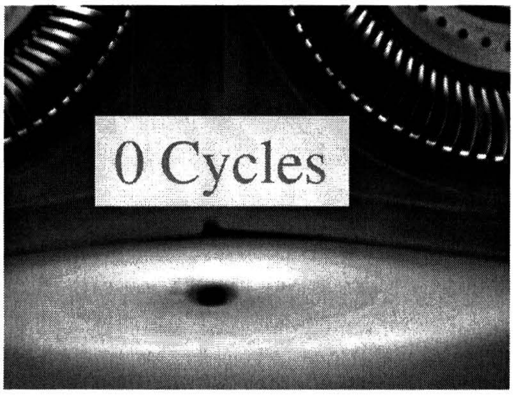
Photo5

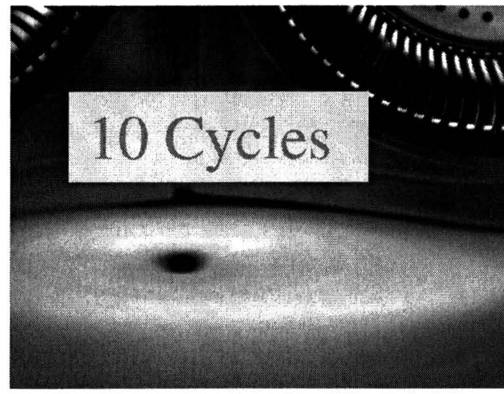

Photo6

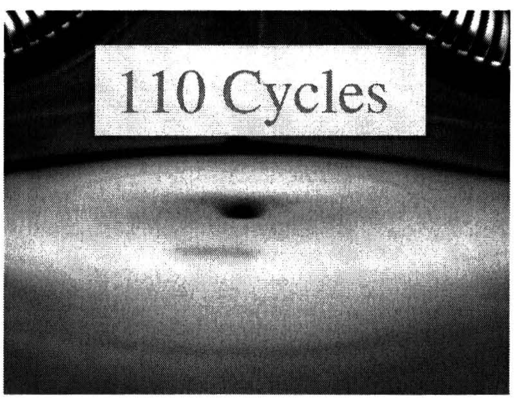
# Appendix K – Pluto pictures III

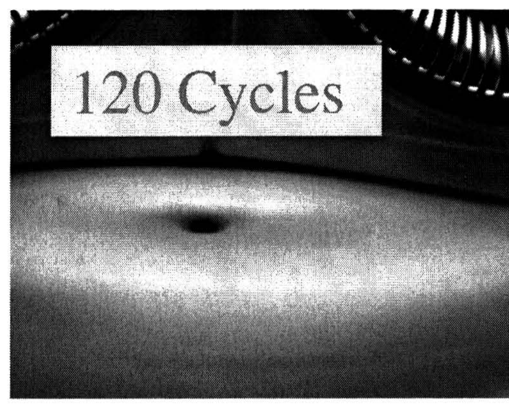


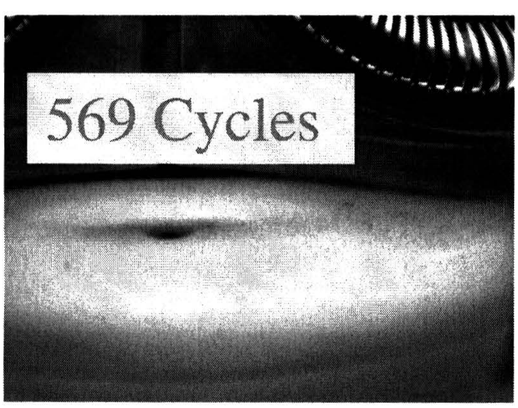
# Appendix L – Pluto in the marathon salon

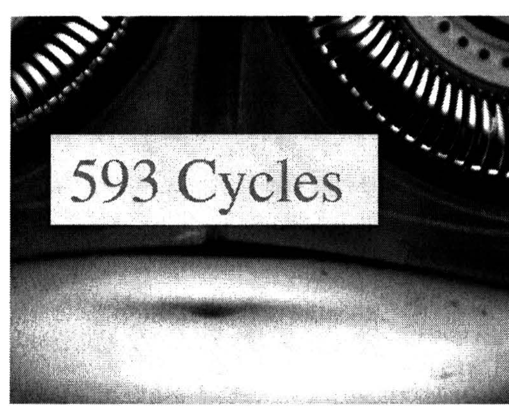


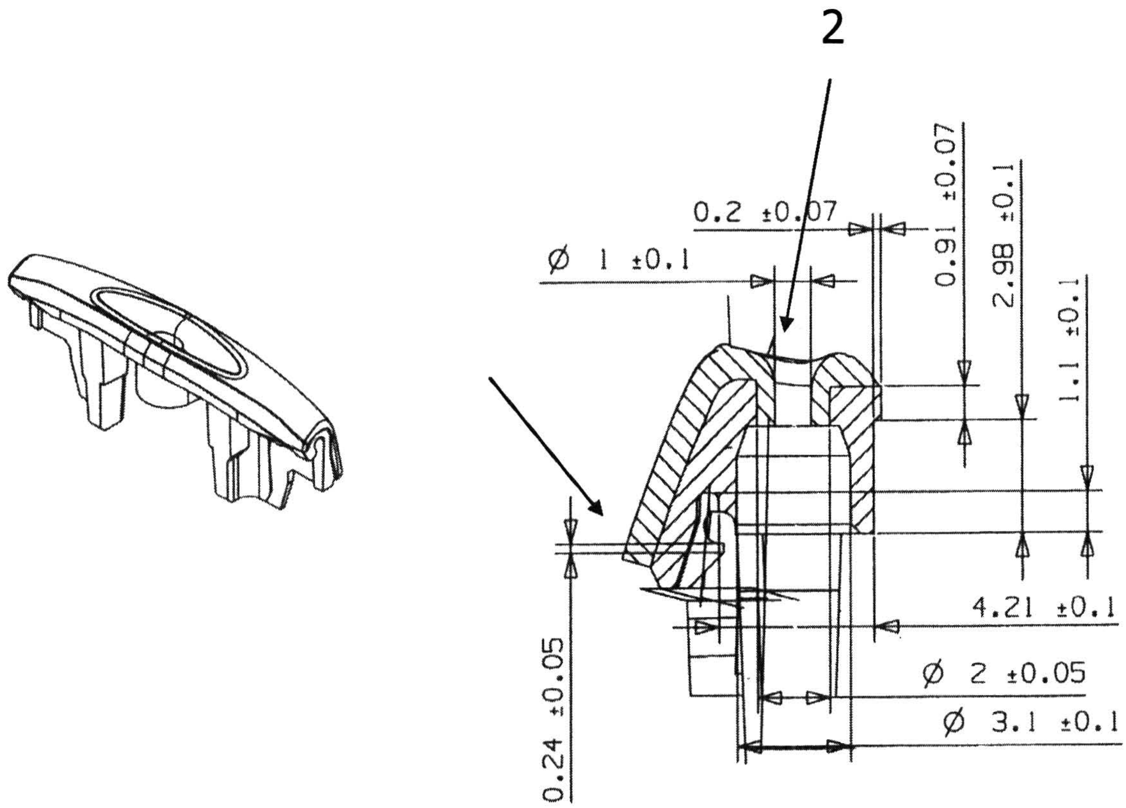



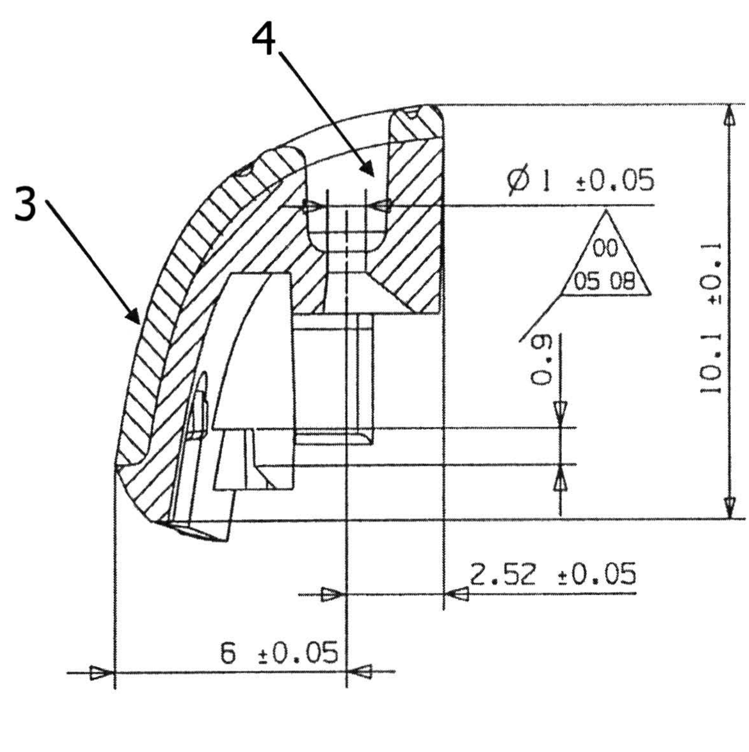



# Appendix M – Nozzle design Pluto & Aquarius



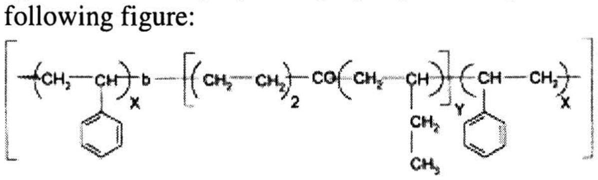
# Appendix N – SEBS

The material of the soft-touch outer layer of the Pluto nozzle is called styrene-ethylene/butylene-styrene (SEBS) and belongs to the family of thermoplastic elastomers (TPEs). The definition of a TPE consists of two parts; the definition of thermoplastics and the definition of elastomers:

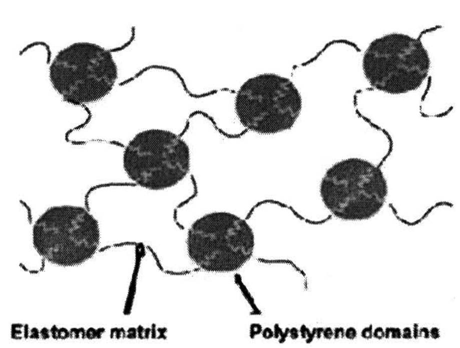
"a polymer blend or compound which above it's melt temperature, exhibits a thermoplastic character that enables it to be shaped into a fabricated article and which, within it's design temperature range, possesses elastomeric behaviour without cross-linking during fabrication. This process is reversible and the products can be reprocessed and remoulded." [BPF03]

*These materials combine the processability of a thermoplastic with the functional performance of a rubber. Such materials are tending to replace traditional rubber in a host of applications offering an easier or cheaper route for producing products which can also be easily be coloured and recycled.*

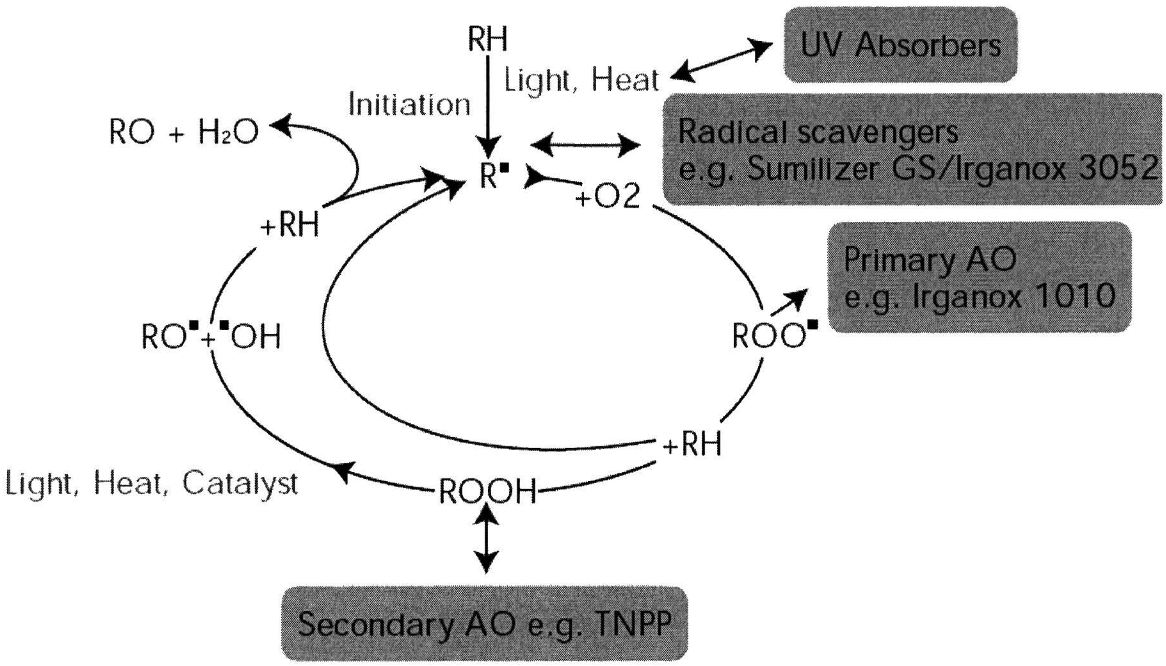
SEBS belongs to the group of styrene based TPEs and is a so-called block copolymer; two hard and rigid ending groups are chemically connected by a flexible and elastic central part. In SEBS case, ending groups are of polystyrene, which present thermoplastic properties: rigidity and fluency. At the elastic central part, which presents rubber properties polyethylene-butylene is used. The chemical structure is shown in the following figure:



One important materials characteristic is that both ending groups are not compatibles with the central part. Therefore, an agglomeration of the ending groups of polystyrene is produced. These points are joined by the elastic central parts, as represented in a simplified fashion in the picture below:

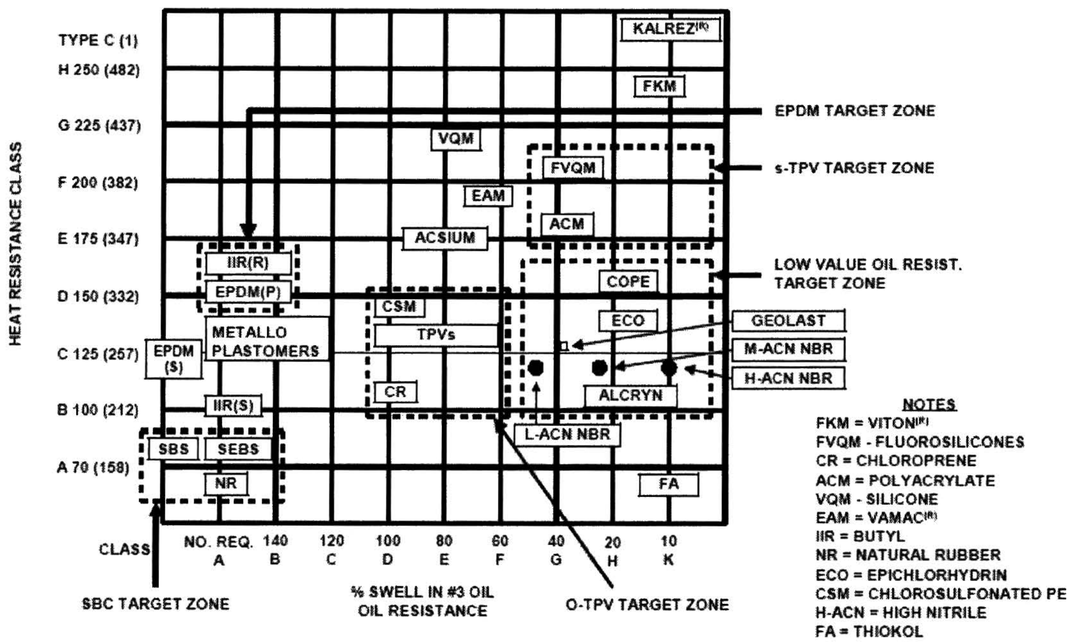


# Appendix O – Degradation Process of SEBS



# Appendix P – SEBS material properties

OIL RESISTANCE/HEAT RESISTANCE OF TPEs AND THERMOSET RUBBERS




SOURCE: ROBERT ELLER ASSOCIATES, INC., TPE MULTICLIENT, 2004

b/mydox/papers/tpebxls04-orhr 04.vsd

ig/myfiles/visio/tpebxls04-orhr 04.vsd

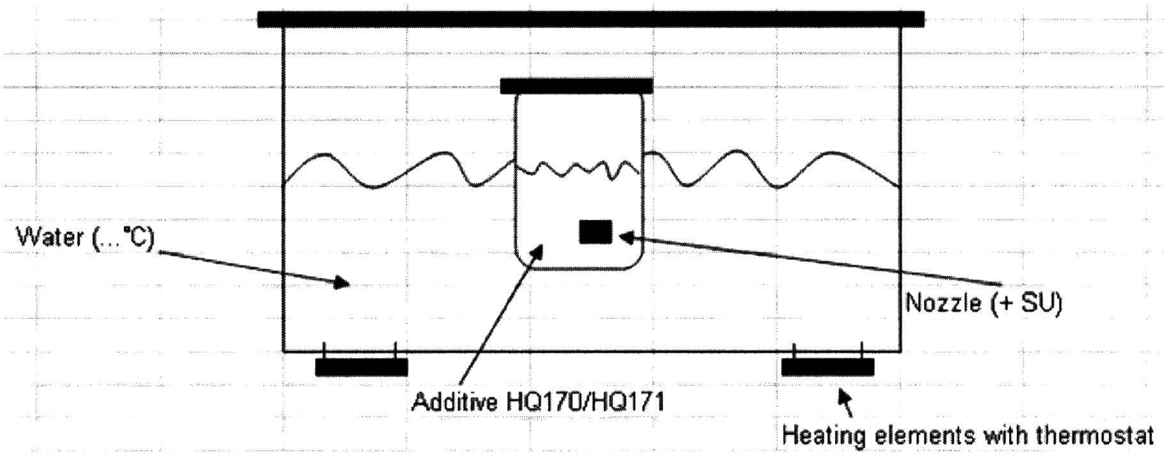
| RTP Series | Base Resin | | Weak Acids | Strong Acids | Weak Alkalis | Strong Alkalis | Organic Solvents | Alcohols | Hydro Carbons | Fuels | Gamma Radiation | UV Radiation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1700 | Modified Polyphenylene Oxide | PPO | E | E | E | E | P | P | F | P | F | F |
| 1800 | Acrylic | PMMA | P | P | G | F | P | P | P | F | G | G |
| 1800 A | Acrylic/Polycarbonate Alloy | PC/PMMA | G | G | G | G | P | F | P | F | F | F |
| 2100 | Polyetherimide | PEI | E | E | E | P | $P^4$ | F | P | F | G | F |
| 2200 | Polyetherehterketone | PEEK | E | E | E | E | E | E | E | G | G | G |
| 2200 A | Polyetherketone | PEK | E | E | E | E | E | E | E | G | G | G |
| 2300 | Rigid Thermoplastic Polyurethane | RTPU | G | G | F | G | $P^4$ | P | P | F | F | P |
| 2500 | Polycarbonate/ABS Alloy | PC/ABS | E | $G^1$ | G | F | $P^3$ | P | P | P | G | F |
| 2700 S | Saturated Styrenic Block Copolymer Thermoplastic Elastomer | SEBS | E | G | E | G | $P^3$ | F | P | P | P | F |
| 2700 U | Unsaturated Styrenic Block Copolymer Thermoplastic Elastomer | SBS | E | G | E | G | $P^3$ | F | P | P | P | P |
| 2800 | Value-Added Thermoplastic Polyolefin Elastomer | TEO | E | G | E | G | $P^3$ | G | $F^7$ | $F^7$ | P | F |
| 2800 D | Thermoplastic Polyolefin Elastomer | TEO | E | G | E | G | $P^3$ | G | $F^7$ | $F^7$ | P | F |
| 2900 | Polyether-Block-Amide Thermoplastic Elastomer | COPA | E | E | E | E | E | E | E | E | F | E |
| 3000 | Polymethylpentene | PMP | E | $G^1$ | E | E | $P^3$ | G | P | F | G | F |
| 3100 | Perfluoroalkoxy | PFA | E | E | E | E | E | E | E | G | G | G |
| 3200 | Ethylene Tetrafluoroethylene | ETFE | E | E | E | E | E | E | E | G | G | G |
| 3300 | Polyvinylidene Fluoride | PVDF | E | E | E | E | E | E | E | G | G | G |
| 3400 | Liquid Crystal Polymer | LCP | E | E | E | E | E | E | E | G | G | G |
| 3500 | Fluorinated Ethylene Propylene | FEP | E | E | E | E | E | E | E | G | F | P |
| 4000 | Polyphthalamide | PPA | E | G | E | G | E | G | E | G | G | F |
| 4100 | Polyetherketoneketone | PEKK | E | E | E | E | E | E | E | G | G | G |
| 4200 | Thermoplastic Polyimide | TPI | E | E | E | E | E | E | E | E | E | E |
| 4300 | Polysulfone/Polycarbonate Alloy | PSU/PC | E | G | G | G | F | G | F | G | F | F |
| 4400 | High Temperature Nylon | HTN | F | P | E | F | G | G | P | G | F | F |
| 4700 | Polytrimethylene Terephthalate | PTT | G | P | P | P | E | G | P | G | G | F |

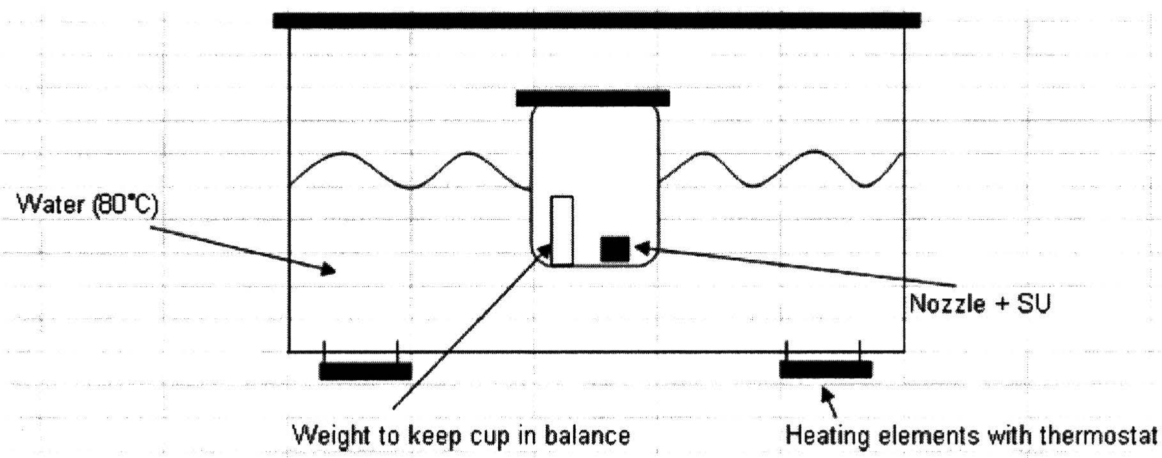
Rev 03/2005

**Ratings**
**E = Excellent**
**G = Good**
**F = Fair**
**P = Poor**

**Notes**
(1) Attacked by oxidizing acids.
(2) Attacked by sulfuric acid.
(3) Soluble in aromatic and chlorinated hydrocarbons.
(4) Soluble in ketones and esters, aromatic and chlorinated hydrocarbons.
(5) Below 176 °F (80 °C).
(6) At ambient temperature.
(7) Property retention with swelling.

# Appendix Q – Test set-up



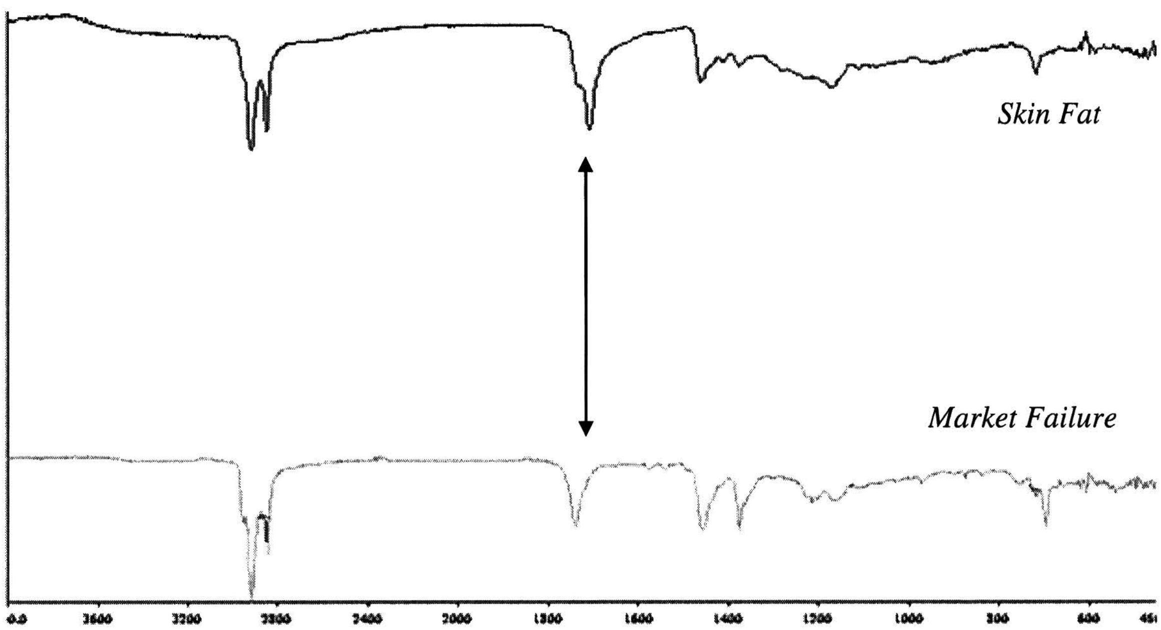
# Appendix R – Results of experiments

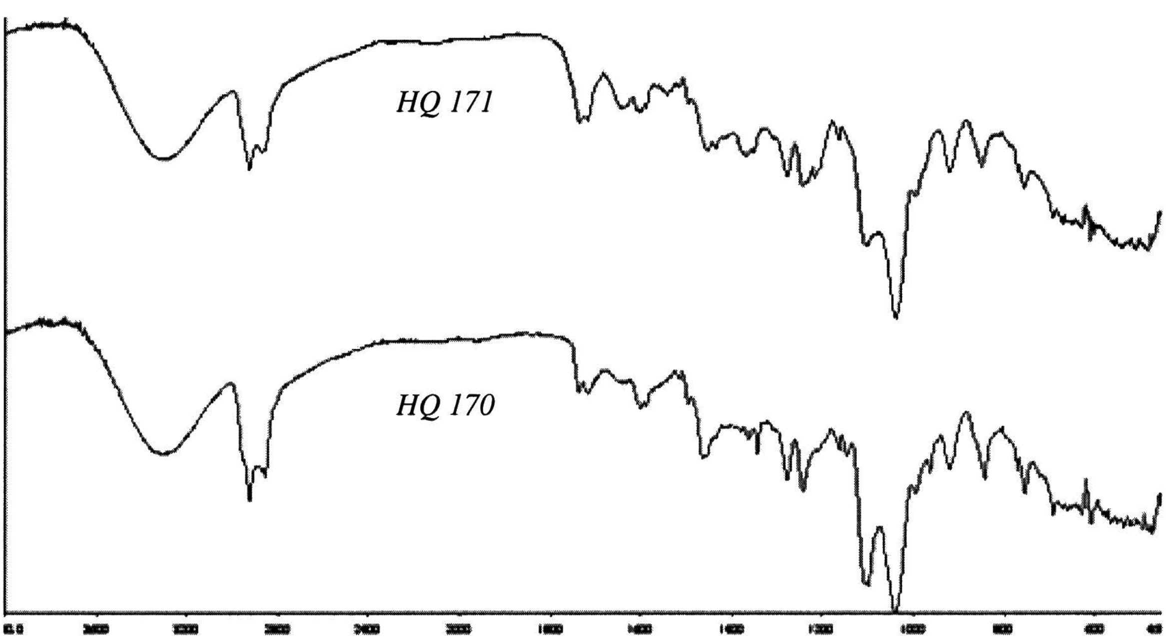
| | Nozzle in HQ 170 | | Nozzle in HQ 171 | |
|---|---|---|---|---|
| | with SU | w/o SU | with SU | w/o SU |
| 0hr. | m = 0.5726<br>Visual: OK | m = 0,5719<br>Visual: OK | m = 0,5718<br>Visual: OK | m = 0,5723<br>Visual: OK |
| 24h.@60?C | m = 0,5803<br>Fun:ok Vis:changed feeling, SU imprint | m = 0,5798<br>Fun:ok<br>Vis:changed feeling | m = 0,5752<br>Fun:ok Vis:changed feeling, SU imprint | m = 0,5786<br>Fun:ok<br>Vis:changed feeling |
| 24h.@70?C | m = 0,5956<br>Fun:ok Vis:changed feeling, SU imprint | m = 0,5912<br>Fun:ok<br>Vis:changed feeling | m = 0,5797<br>Fun:ok Vis:changed feeling, SU imprint | m = 0,5849<br>Fun:ok<br>Vis:changed feeling |
| 24h.@80?C | m = 0,6057<br>Fun:ok Vis:changed feeling, SU imprint | m = 0,6032<br>Fun:ok<br>Vis:changed feeling | m = 0, 5843<br>Fun:ok Vis:changed feeling, SU imprint | m = 0,5903<br>Fun:ok<br>Vis:changed feeling |

Nozzle with skin fat (sebum)

| | @80?C | | @21?C | |
|---|---|---|---|---|
| | with SU | w/o SU | with SU | w/o SU |
| 0h. | m = 0,5715<br>Fun: ok<br>Vis: ok | m = 0,5721<br>Fun: ok<br>Vis: ok | xxxxx xxxxx<br>xxxxx xxxxx<br>xxxxx xxxxx | m = 0,5713<br>Fun: ok<br>Vis: ok |
| 24h. | m = 0,6161<br>Fun: not ok, closed<br>Vis:all symptoms | m = 0,6149<br>Fun: not ok, closed<br>Vis:all symptoms except SU imprint | xxxxx xxxxx<br>xxxxx xxxxx<br>xxxxx xxxxx | m = 0,5761<br>Fun:ok<br>Vis:discoloured |
| 48h. | experiment stopped | experiment stopped | xxxxx xxxxx<br>xxxxx xxxxx<br>xxxxx xxxxx | m = 0,5832<br>Fun:ok<br>Vis:discoloured |

# Appendix S – Infrared spectra



# Appendix T – Database of failure mechanisms

| Stress factors | Failure Mechanism |
|---|---|
| ***Mechanical (tensile/compressive/shear):*** | |
| Overstress | Fracture |
| Cyclical stress | Fatigue -> Fracture |
| Continuous/cyclic tensile stress + high temperature | Creep |
| Friction (lateral stress) | Wear (=removal of material from the surfaces of parts as a result of their movement to other parts)<br>Different forms of wear are: Adhesive wear, fretting, abrasive wear, fluid erosion, cavitation and corrosive wear |
| Vibration & Shock | Fracture due to fatigue, or due to mechanical overstress<br>Wear of components such as bearings, connectors, etc.<br>Loosening of fasteners, such as screws, bolts, etc.<br>Acoustic noise |
| ***Temperature:*** | |
| General | Expansion or contraction -> mechanical stress |
| High Temperature | Softening and weakening<br>Melting<br>Charring<br>Other chemical changes<br>Reduced viscosity or loss of lubricants<br>Interaction effects (e.g. temperature accelerated corrosion) |
| Low Temperature | Embrittlement of plastics, increasing viscosity of lubricants, condensation, and freezing of condesation or coolants |
| ***Humidity & Condensation:*** | |
| | oxidation (corrosion) |
| | Short-circuiting of electrical systems |
| If contamination is also present | Chemical corrosion |
| By providing an electrolyte | Electrolyte corrosion |
| ***Electronics and Electrical Stress:*** | |
| | Electrolytic corrosion |
| Current | Rising temperatures -> melting point conductor-> fuse<br>Thermal damage to other parts<br>Drifting of component parameter values (e.g. resistance)<br>Creation of magnetic fields |
| Voltage | High-voltage -> current overstress<br>Arcing<br>Corona discharge |
| High Temperature | Insulation charring -> Wire coils short-circuited |
| Low Temperature | parametric changes in electrical characteristics |
| Repeated temperature changes | fatigue damage and creep of wire bonds and soldier joints |
| Electric power | Heat -> ..... |