The design of an accelerated test method to identify reliability problems during early phases of product development

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The design of an accelerated test method to identify reliability problems during early phases of product development

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Eindhoven, op gezag van de Rector Magnificus, prof.dr.ir. C.J. van Duijn, voor een commissie aangewezen door het College voor Promoties in het openbaar te verdedigen op donderdag 23 februari 2006 om 16.00 uur

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Gembong Baskoro

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God Bless You All!
Eindhoven, February 2006
This thesis is dedicated specially also to

In memory of my father:

_Who has dedicated his life to teach people and his children
The truth, the strength, the right, the knowledge, and the freedom_

ir. Sardji Kartosudiro†

My mother:

_Who always remains calm and stands firm during difficult times_

Nurmiah Sardji

My family:

_Who give meaning to my life_

Europa Herfani Baskoro (3rd daughter)
Jayanti Aarnee Kusumadewi (2nd daughter)
Indah Purnamaningtyas (1st daughter)
Endang Purwantini (wife)

My Brothers and Sisters & their family:

_Who lived with me along day and night for almost 20 years in (west) Timor Island_

Wiwick Ayuningsih & Wahyu,
Legowo Budianto & Ida,
Leo Santo Sudiro & Silvi,
Yenny Emilia & Frits
Munik Saryati, Jan Sibu, Ano, Ipi

† 01-03-1937 - † 25-03-2003
SUMMARY

In order to achieve customer satisfaction, it is necessary that products not only work at the moment they are sold to a customer, but that these products are also able to meet with customer requirements for a certain period of time. This characteristic is also known as “product reliability”. One method to ensure product reliability is to analyze the expected product reliability already during the product development process. It can be done by testing the product's compliance to specifications during and after the manufacturing processes. In practice however, this concept is not working well because increasingly complex products and time-to-market pressures lead to less time for (increasingly complex) verification/validation processes (testing). As this thesis will demonstrate, there is slippage of unreliable products to customers. This is indicated by an increasing number of customer complaints. It is not unusual that these complaints from customers lead to products returned for a repair. If this non-compliance is not related to a violation of product specifications, it is likely that the service organization performing the requested repair will not be able to identify the cause of the problem. As this thesis demonstrates, this is quite likely since same verification/validation references are used in the repair process as used already earlier during the manufacturing.

This thesis defines NFF and/or CNF as a problem in a product, initiated by a customer complaint, where the cause of the failure cannot be found during technical examination of the product. In cases where an abnormality can be found in the product but not a cause, the event is called Cause-Not-Found (CNF). In cases where the customer complaint can not be related to an abnormality in the product, the event is called No-Fault-Found (NFF). Both NFF and CNF are unacceptable in terms of business/quality management, because they constitute an uncontrolled business process (when a cause of a failure can not be found, it is likely that the same failure re-appears in future generations of products). Such an uncontrolled process can damage customer/brand name.

In reliability test methods described in literature, the technical examination is aimed to validate the functionality of the product according to a set of specifications. Therefore, during the test, the technical specification is used as a reference to determine the existence of problems in a product. If a product is not able to meet its technical specification, then this product has problems known as hard reliability problems. This thesis focuses on hard reliability problems because although the problems may appear during the usage of the product, the problems may have been initiated during the product development process (PDP). Therefore, logically the problems can be tackled during the product development process. This thesis specifically concentrates on the hard reliability problems that are categorized as class 1 and/or class 2 failures in the four-phase rollercoaster model and known as early failure hard reliability problems (Wong, 1988).

Based on the analysis summarized above, an alternative testing concept has been developed. This concept focuses on the identification and elimination of time-independent hard NFF reliability problems and is designed to be used in the early Product Development Process. Although the new testing concept is conceptually more
The thesis uses the following research questions to address hard NFF reliability problems:

1. *Do the class 1 and/or class 2 failures, time independent hard NFF problems, in the context of the four-phase rollercoaster model exist?*

2. *Is it possible to identify, and prevent class 1 and 2 hard reliability problems in the early product development process?*

This research demonstrates, for research question 1, that the early failure time-independent reliability problems exist in the field in a realistic industrial context. To help answer the research question 2, this research uses the Q&R reference model developed by Brombacher et al. (2005) to develop a classification model for time independent hard reliability problems. This classification model is used as a basis for the development of a new test concept called Multiple Environment Stress Analysis (MESA). In this thesis the development of MESA has been split in two steps. The first step focuses on the development of MESA, and the second step focuses on the implementation and application of MESA.

In the first step, the concept of MESA is developed based on the principles of an engineering analysis test. Engineering analysis test is a test concept that uses engineering knowledge during the test followed by the analysis of the test result. Among others the engineering knowledge includes the knowledge of product failure mechanism, the knowledge of design of experiments, the knowledge of accelerated testing, and the knowledge of test equipment. This thesis demonstrates in case studies that having previous knowledge of failure mechanism ensures the success of the test. The case studies demonstrate that MESA is able to deliberately activate a traditional NFF field failure under laboratory conditions when the failure mechanism is previously known. In this way it is possible to gain a far better understanding on the way complex dynamic stressor sets are involved in the occurrence of field failures. A second field case study demonstrates that MESA is also able to activate failure from a product/module where the field failure is known but the underlying field failure mechanism was previously unknown.

The second part of this thesis focuses on MESA application in the context of an industrial product development process. The second step aims to explore the applicability of MESA as a test method during the PDP. For this purpose MESA was applied on a product in the (early) development phases. During this step the potential for integration of MESA into existing test methods was explored. Due to practical limitations, this research explores the second step only in a limited number of cases. The first priority of attention is to find the early failure hard reliability problems on a product that is in the development phases. The focus is specifically on the class 1 and/or class 2 failures in the four-phase rollercoaster model. Therefore, application of MESA in the existing testing scheme in PDP is considered as the second priority. For the first priority, as an answer of the research question 2, this research shows within
limited cases that it is logically possible to prevent hard reliability problems in the early PDP. However, the second priority, the adaptation of MESA into existing test methods still requires further study.
SAMENVATTING

Om klantentevredenheid te verkrijgen, moeten producten niet alleen werken op het moment dat ze aan de klant verkocht worden, maar ze moeten ook nog aan klanteneisen blijven voldoen gedurende een bepaalde tijdsperiode. Deze karakteristiek is ook bekend als bedrijfszekerheid (reliability). Een methode om de bedrijfszekerheid van een product te waarborgen, is het uitvoeren van een bedrijfszekerheidsanalyse tijdens het product ontwikkelproces. Dit kan uitgevoerd worden door te testen of producten voldoen aan specificaties gedurende en na het productieproces. In de praktijk werkt dit concept niet echt goed omdat de toenemende complexiteit van producten en druk op 'time-to-market' leiden tot steeds minder tijd voor (complexer wordende) verificatie/validatie processen (testen). Zoals dit proefschrift laat zien, bereiken (producten met-) bedrijfszekerheidsproblemen de klant. Dit blijkt uit toenemende aantallen klantenklachten. Het is niet ongewoon dat dit leidt tot producten die door de klanten worden geretourneerd voor reparatie. Het probleem is dat, als de klacht niet gerelateerd is aan (niet voldoen aan) productspecificaties, de service organisatie de oorzaak van het probleem niet kan identificeren. Zoals dit proefschrift laat zien, is dit in de huidige industriële context zeer waarschijnlijk, omdat dezelfde verificatie/validatie specificaties worden gebruikt bij het reparatieproces als al eerder bij de productie.

Dit proefschrift definiert NFF en/of CNF als een probleem in een product, geïnitieerd door een klacht van een klant, waarbij de oorzaak van het probleem niet gevonden kan worden bij een technisch onderzoek van het product. In gevallen waarbij een afwijking in het product gevonden wordt, maar geen oorzaak, is er sprake van 'Cause-Not-Found' (CNF). In gevallen waarbij er geen relatie is tussen klantenklacht en een afwijking in het product is er sprake van 'No-Fault-Found' (NFF). Zowel NFF als CNF zijn onacceptabel in termen van bedrijfs/kwaliteitsmanagement, omdat zij leiden tot een onbeheersbaar bedrijfsproces; als de oorzaak van een klacht niet gevonden wordt, is het waarschijnlijk dat hetzelfde probleem opnieuw optreedt in volgende generaties producten. Een dergelijk onbeheerst bedrijfsproces kan leiden tot schade aan het klant/merk image.

Bij reliability test methodes beschreven in de literatuur, wordt het technische onderzoek gebruikt om de functionaliteit van het product te valideren conform een set van specificaties. Daarom wordt gedurende een test de technische specificatie gebruikt om vast te stellen of er problemen in een product aanwezig zijn. Als een product niet conform technische specificaties is, heeft het product fouten genoemd harde reliability fouten. Dit proefschrift focuseert op harde reliability problemen omdat ondanks dat de problemen zichtbaar kunnen worden tijdens het gebruik van een product, deze problemen geïnitieerd kunnen zijn gedurende het product ontwikkelproces (Engels: 'Product Development Process' afgekort PDP). Om deze reden moet deze problemen ook tijdens het product ontwikkelproces worden aangepakt. Dit proefschrift concentreert zich specifiek op klasse 1 en 2 van het vierfasen 'rollercoaster' model, ook bekend als vroege harde reliability problemen (Wong,1988)
Gebaseerd op de analyse hierboven samengevat, is een alternatief test concept ontwikkeld. Dit concept richt zich op de identificatie en eliminatie van tijdsafhankelijke harde NFF reliability problemen en is ontworpen om gebruikt te worden vroeg in het product ontwikkelproces. Ondanks dat het concept conceptueel gecompliceerder is, heeft het aanzienlijke voordelen vergeleken met bestaande test concepten. De voordelen van het alternatieve test concept zijn: (1) effectiever in termen van afgedekte fouten, (2) vanwege de systematische, geautomatiseerde aanpak even efficiënt als recente test concepten en (3) het concept kan gebruikt worden vroeg in het product ontwikkelproces.

Dit proefschrift gebruikt de volgende onderzoeksvragen om harde NFF reliability problemen aan te pakken:

1. Bestaan klasse 1 en/of 2 tijdsafhankelijke harde NFF problemen in de context van het vier-fasen 'rollercoaster' model?
2. Is het mogelijk om klasse 1 en 2 harde reliability problemen te voorkomen vroeg in het product ontwikkelproces?

Dit onderzoek laat met betrekking tot onderzoeksvraag 1 zien dat vroege, faaltijd onafhankelijke, reliability problemen in het veld in een realistische industriële context bestaan. Als hulp bij het antwoorden van onderzoeksvraag 2 is het Q&R referentie model ontwikkeld door Brombacher et al. (2005) gebruikt als basis voor een classificatie model voor tijdsafhankelijke harde reliability problemen. Dit classificatie model is gebruikt als basis voor de ontwikkeling van een nieuw test concept genoemd 'Multiple Environment Stress Analysis (MESA)'. In dit proefschrift wordt de ontwikkeling van MESA gesplitst in twee stappen. De eerste stap focust op de ontwikkeling van MESA en de tweede op de implementatie en toepassing van MESA.

In de eerste stap is het concept van MESA ontwikkeld, gebaseerd op de principes van een zogenoemde 'engineering analysis test'. Deze 'engineering analysis test' is een test concept dat gebruik maakt van technische kennis en ervaring gedurende de test, gevolgd door de analyse van het testresultaat. Deze technische kennis houdt onder andere in kennis van product faalmechanismen, kennis van het opzetten van experimenten, kennis van versneld testen en van test apparatuur. Dit proefschrift laat met case studies zien dat voorkennis van faalmechanismen leidt tot een succesvolle test. De case studies laten zien dat MESA doelbewust een traditionele NFF veldfout kan activeren onder laboratorium condities, als het bijbehorende faalmechanisme van tevoren bekend is. Op deze manier is het mogelijk om veel beter inzicht te krijgen in manier waarop de set van complexe dynamische stressoren het voorkomen van de veldfout beïnvloeden. Een tweede case studie laat zien dat MESA ook faalmechanismen kan activeren van een product/module waarbij de veldfout bekend is, maar het onderliggende faalmechanisme niet.

Het tweede deel van dit proefschrift focuseert op de toepassing van MESA in de context van een industrieel product ontwikkelproces. In de tweede stap wordt gestreefd de toepasbaarheid van MESA gedurende het PDP te onderzoeken. Voor dit doel is MESA toegepast op een product in de vroege product ontwikkelingsfases. Gedurende deze stap is de integratie van MESA met bestaande test methodes onderzocht. Door praktische beperkingen is de tweede stap slechts in een beperkt
aantal cases onderzocht. De eerste prioriteit bij het onderzoek is het vinden van vroege harde reliability problemen bij een product dat nog in de product ontwikkelingsfase zit. De focus is specifiek op klasse 1 en 2 fouten in de vier-fasen 'rollercoaster curve'. Inpassen van MESA in bestaande test schema's is als tweede prioriteit genomen. Voor de eerste prioriteit, als antwoord op onderzoeksvraag 2, laat dit onderzoek zien dat binnen een beperkt aantal cases het logischerwijs mogelijk is om harde reliability problemen vroeg in het PDP te voorkomen. De tweede prioriteit, het inpassen van MESA in bestaande test methodes echter, behoeft nog verder onderzoek.
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**NOMENCLATURE**

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<tbody>
<tr>
<td>ALT</td>
<td>Accelerated Life Test</td>
</tr>
<tr>
<td>AST</td>
<td>Accelerated Stress Test</td>
</tr>
<tr>
<td>CND</td>
<td>Can Not Duplicate</td>
</tr>
<tr>
<td>DOA</td>
<td>Dead on Arrival</td>
</tr>
<tr>
<td>DoE</td>
<td>Design of Experiments</td>
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<tr>
<td>DFM</td>
<td>Design for Manufacturability</td>
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<td>DFT</td>
<td>Design for Test</td>
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<td>DFX</td>
<td>Design for eXcellence</td>
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<td>Field Call Rate</td>
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<td>HALT</td>
<td>Highly Accelerated Life Test</td>
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<td>HAST</td>
<td>Highly Accelerated Stress Test</td>
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<td>HASS</td>
<td>Highly Accelerated Stress Screening</td>
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<tr>
<td>ICM</td>
<td>Identify-Communicate-Mitigate</td>
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<td>IRIS</td>
<td>International Repair Information Service</td>
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<td>MEOST</td>
<td>Multiple Environment Overstress Test</td>
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<td>MESA</td>
<td>Multiple Environment Stress Analysis</td>
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<td>MISMOP</td>
<td>Month in Service Month in Production</td>
</tr>
<tr>
<td>MPOSOT</td>
<td>Maximum Practical Overstress Test Limit</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>NAD</td>
<td>No Apparent Defect</td>
</tr>
<tr>
<td>NEOF</td>
<td>No Evidence of Failure</td>
</tr>
<tr>
<td>NFF</td>
<td>No-Fault-Found</td>
</tr>
<tr>
<td>NPD</td>
<td>New Product Development</td>
</tr>
<tr>
<td>NPF</td>
<td>No Problem Found</td>
</tr>
<tr>
<td>NTF</td>
<td>No Trouble Found</td>
</tr>
<tr>
<td>ORT</td>
<td>Ongoing Reliability Test</td>
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<tr>
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<td>Plan-Do-Check/Study-Act</td>
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<td>Product Development Process</td>
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<td>Product Life Cycle</td>
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<tr>
<td>Q&amp;R</td>
<td>Quality and Reliability</td>
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<td>Quality Function Deployment</td>
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<td>Retest OK</td>
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<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>SMART</td>
<td>Specific Measurable Achievable Realistic and Time-bounded</td>
</tr>
<tr>
<td>STRIFE</td>
<td>Stress plus Life Testing</td>
</tr>
<tr>
<td>TNI</td>
<td>Trouble Not Identified</td>
</tr>
<tr>
<td>TTM</td>
<td>Time to Market</td>
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<tr>
<td>TTP</td>
<td>Time to Profit</td>
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CHAPTER 1 INTRODUCTION

1.1. Introduction

A company’s ability to achieve and/or maintain competitiveness in the current market depends on their industrial performance and their ability to successfully develop and introduce new products. Brombacher et al. (2005) defined that modern product creation processes, for strongly innovative consumer products, have been dominated by four trends: They are (1) Innovation (influx of new technology), (2) pressure on time to market, (3) increasing customer demands, and (4) globalization.

The important influence of innovation, combined with a strong pressure on time-to-market is that products can be economically obsolete and out-of-date before the end of their technical life. Products can become obsolete and outdated as soon as newer, more innovative products enter into the same market. Therefore, to survive in such a highly competitive market, manufacturers must deliver their new products within a short market window, preferably before their competitors arrive. The ability to use market windows for new technology in an appropriate manner may make a difference between being a market leader and losing a market. When such a market window is missed, competition on price may be the only alternative manner to gain market share. This combination of factors puts a considerable strain on manufacturers in these highly innovative (and competitive) fields.

An additional, complicating, factor is the role of the customer. For increasingly complex products, customers more and more ignore product specifications and judge the quality and reliability on the ability of this product to meet with their, often implicit, requirements and expectations. (Jacobs, 1999; Brombacher, 2000). The fact that customer complaints relate increasingly to implicit requirements will, without additional precautions, lead to a situation where field information of increasingly complex products will get less and less detailed. (Den Ouden et al., 2005)

From manufacturers perspective it will therefore become increasingly difficult to realize reliable products within a given budget in a given amount of time. Since manufacturers have less information in less time relating to increasing complex products (Brombacher, 2000) this can easily lead to reliability problems getting “out of control”. In practice, the product reliability problems such as No-Fault-Found
(NFF\textsuperscript{1}) account up to 50\% of the field problems for new products (Brombacher, 2000). This figure indicates that the existing quality assurance concepts are not sufficient to reduce NFF problems.

Therefore, the objective of this research is to tackle the NFF problems by developing an alternative quality assurance concept based on a new approach for product testing. It focuses especially on early failure problems as defined by class 1 and/or class 2 failures of the four-phase rollercoaster model (Yuan, 2002; Petkova, 2003). The reason to focus on class 1 and/or class 2 failures is because if considering the four trends issues, as indicated previously, then the end-of-life of a product is no longer relevant on the application area of consumer products. The detail discussion on this topic appears in section 2.4.

1.2. Structure of this Thesis

This thesis will explain in more detail the development of an alternative test concept that will be used to identify early failures, such defined as class 1 and/or class 2 failures in the four-phase rollercoaster model (Brombacher et al., 2005).

In chapter 2 the relation between reliability, product life cycle, and product creation process is reviewed. A classification model is introduced and used to help focusing the research. This classification model, that can be used to explain a wide range of reliability problems, is also known as the quality and reliability reference model (Brombacher et al., 2005).

Chapter 3 reviews recent trends in the development of products that affect reliability. It addresses trends in product innovation processes, effects of business pressures to reliability problems, and the importance of information in reliability problems prevention. Finally this chapter discusses research objective, research questions, and research methodology.

The focus of chapter 4 is on the class of so-called unknown reliability problems. It will be shown by means of a case study that unknown failures form an increasing problem in an actual industrial situation.

Chapter 5 develops an analysis framework to assess the existing test methods. Before presenting the assessment of different testing concepts, this chapter discusses the classification, the description, and the criteria for testing concepts.

Chapter 6 provides in details the development of a new testing method called MESA. Included in the discussion are the concept, the objective, the method, the theory, the test protocol, and the implementation.

In chapter 7, MESA is implemented and a MESA case study is evaluated. This chapter provides the results of cases and evaluation of MESA in an industrial context.

Finally, chapter 8 summarizes the conclusions and presents recommendations for future research.

\textsuperscript{1}) a detail discussion on NFF is given in chapter 4,
CHAPTER 2 WHAT IS RELIABILITY?

The purpose of this chapter is to define a model that can assist in focusing on specific reliability problems. For this reason, this chapter adopts a model defined by Brombacher et al. (2005). The model, the quality and reliability reference model, is not only facilitates the understanding of reliability problems but also helpfully separates them from broader reliability issues. Before presenting the model, this chapter addresses the following topics: reliability, reliability and the product life cycle, reliability and the product development process, and methods of classifying reliability problems.

2.1. Reliability

This thesis only deals with reliability instead of quality, because the dimensions of quality are ambiguous. According to Garvin (1988), Rosenthal (1992), and Rosenau and Moran (1993), the quality dimensions that are used to judge a product cover broad aspects. Garvin (1988) and Rosenthal (1992) listed quality dimensions as follows:

(1) Performance (Product primary operating characteristics)
(2) Features (Supplementary characteristics of a product)
(3) Reliability (Product consistency over time)
(4) Conformance (Meeting industry or established standard)
(5) Durability (Measure of product useful life)
(6) Serviceability (Ease-of-repair)
(7) Aesthetics (Product appearance)
(8) Perceived Quality (Subjective reputation of a product)

Instead of perceived quality, as defined 8th in the list by Garvin (1988) and Rosenthal (1992), Rosenau and Moran (1993) defined it as

(8) Response (Timeliness or professionalism), and
(9) Reputation (Past performance).

Therefore, it is possible that the use of the terms quality and reliability can be misleading.
2.1.1. Reliability - Common Definition

A common definition of reliability is the ability of a product or system to fulfill its intended purpose for a certain period of time under stated conditions. This definition contains the term “intended purpose” which in itself is ambiguous; often the intended purpose is interpreted as the product specifications. Brombacher (2000) has argued, especially for innovative high-volume consumer products, that the intended purpose for a user is different from that for a manufacturer. When a product works according to its technical specifications but a user is unhappy with the functionality, the user will be dissatisfied with the product quality and reliability. In this example, the reason of dissatisfaction is not because the product is violating its technical specifications but because the product only fulfils part of the customer requirements. Therefore, using the earlier definition of reliability requires a more thorough understanding of the customer requirements.

2.1.2. Customer Requirements

Before going into detail, the terms of “user”, “customer”, and “consumer” must be clarified. A customer is the person, or persons, for whom the product is intended, and usually (but not necessarily) who (finally) decides the requirements (IEEE Std 1219-1992). The term of customer, in IEEE STD 1219-1992, makes no distinction whether the person is the direct purchaser or only the user. In reality, the term of customer can be used both for persons and for business organizations. For example, a supermarket that purchases a product from a manufacturer is also a customer. Similarly, a user is the person, or persons, who operates or interacts directly with the system (IEEE std 1219-1992). In addition, a consumer is the person who uses the product even if (s)he has not purchased the product (Marketing source). This thesis will use the terms of “customer”, “user”, and “consumer” with the same meaning, regardless of the distinction of the purchaser. Therefore, the customer is a purchaser, a user, and/or a consumer of a product.

In the rest of this thesis, the term of “customer” will be used. In practice, the needs of the customer must seriously be taken into consideration. These needs have been widely known as customer needs, customer requirements, or customer attributes (Wheelwright & Clark, 1992; Ulrich & Eppinger, 2000). This thesis will only use the term of customer requirements, because the term of customer needs, customer requirements, and customer attributes are similar. Moreover, Ulwick (2002) defined customer requirements as the types of information for solutions, design specifications, customer needs, and customer benefits. This information is obtained by listening to the customers. The process of listening to the customers is widely known as capturing “the-voice-of-the-customers”. The information always is useful, even if it does not result in the identification of every need the new product will address (Ulrich & Eppinger, 2000). Furthermore, customer requirements can also be defined by brainstorming; this can involve a cross-functional team, or other tools (Wheelwright & Clark, 1992). However, this classical definition of customer requirements will not be used in this thesis. On the contrary, this thesis will use the term of customer requirements in a different way. The customer requirements can be identified by evaluating how customers are disappointed by a product expressed in a customer complaint. Therefore, the aspects of customer complaint are the customer
requirements. Sander and Brombacher (2000) define five aspects that can lead to formal customer complaints:

a) The product is not safe.
b) The product does not work.
c) The product does not comply with specifications.
d) The product does not meet customer expectations.
e) The product does not have sufficient satisfying aspects.

It is important to note that although part or all of the above aspects are not met, customers will not automatically deliver complaint. It is especially if customers do not experience problems in the product. The mechanism of complaint behavior is described in the following section.

2.1.3. Complaints and Reliability

In the past, if a customer bought a product that did not function (either immediately or after some time) then the customer could choose to take action by making a complaint. Alternatively, no action was taken if (s)he felt it was not a problem (Broadbridge & Marshal, 1995). In today’s business practices, however, customers are encouraged to make a complaint by the manufacturer of the product whenever they are dissatisfied with the product. Customers not only also have the right to make a complaint but to get their money back if problems occur within legal guarantees (warranty) period (Directive 1999/44/EC; Sander & Brombacher, 2000; Petkova, 2003). In European Countries (EC), for example, the rights of customers are protected by law and regulated in EC-directives (Directive 1999/34/EC; Directive 1999/44/EC). The directives are adopted and implemented in national law by the member states. To resolve the complaint, the manufacturer or the seller usually will replace the faulty product with another one. In the worst case, the settlement of the complaint can be irritating and costly. For example, a customer can take public action, such as legal action, complain to a government agency, or seek compensation (Broadbridge & Marshal, 1995; Directive 1999/44/EC). In customer complaint settlement the terms of “producer”, and “seller” must be clear, because each of them has a different legal responsibility in the complaint settlement. The producer can be (1) the manufacturer of consumer goods, (2) the importer of consumer goods into the territory of the community, or (3) any person purporting to be a producer by placing his name, trademark, or other distinctive sign on the consumer goods. The meaning of the seller is any natural or legal person who, under a contract, sells consumer goods in the course of his trade, business, or profession (Directive 1999/44/EC). The focus of this thesis only deals with reliability problems not with the complaint settlement. Therefore, this thesis uses the term of “manufacturer” to mean the direct producer of the product that has a causal relationship with reliability problems. To deal with the complaint, therefore, it is necessary to understand the mechanism of the complaint behavior. A customer will complain under the following conditions:

1. When the customer requirements are fulfilled but customers are dissatisfied with the product.
2. When part or all of the customer requirements are not fulfilled; this situation triggers customers to complain if they feel this is a problem.
3. It is also possible that part or all of the customer requirements are ignored and the customer is dissatisfied with the product but the customer files no complaint.

The conditions indicate that the complaint behaviors are triggered by the perceived reliability problems of the customer, expressed as customer dissatisfaction. The problems are not merely because of product error. It is possible that the perceived reliability problems that cause the customer to complain are beyond the manufacturer and/or customer’s knowledge or understanding. Therefore in the classical approach, a customer complaint was considered as an indication of reliability problems. This thesis, however, no longer considers the customer complaints as an indication of problems, as used in the classical approach. Customer complaints are considered to be related to the true reliability problems. However, the customer can complain, meaning that the product has failed to fulfill part or all of the customer requirements, even though the manufacturer has no other knowledge of the problems. In practice, the vital customer requirements, such as requirements of product safety and product workability, are protected by law known as the customer rights (Directive 1999/44/EC). This implies that the customer complaint not only can lead to non-compliance of the product but to violation of the law. This thesis only deals with the reliability problems that lead to customer complaints as in condition 2. To deal with this situation, the manufacturer needs to ensure that the product is free from reliability problems before the customer purchases it. For this reason, the manufacturer has to understand the reliability problems (see section 2.4.2.). However, firstly it is important to understand the adapted term of reliability and customer requirements as described in the following section.

2.1.4. New Definition of Customer Requirements and Reliability

Sections 2.1.1. and 2.1.2. have presented the common definition of reliability and customer requirements. Considering the above, we have to align the terms to the customer requirements as defined by Sander and Brombacher (2000). Therefore, this thesis redefines customer requirements as the fulfillment of all the aspects defined by Sander and Brombacher (2000) (see also page 6). Similarly, reliability is redefined as the fulfillment of the customer requirements over time and under stated conditions. Although there is no clear-cut for the fulfillment of customer requirements, the legal warranty time can be used as representative of time. The reason is that the legal warranty time is a legal bound between customer and manufacturer. Moreover, if customer requirement is not fulfilled during warranty time then there is a possible risk of warranty claims by customer (as indicated in section 2.1.3.). Therefore, the legal warranty time is the minimum time required by manufacturer to secure customer requirements. In fact, these definitions correspond to the reality that customer requirements have strong causal relationships to the product reliability (see section 2.4.). The next section presents the relation of reliability with the product life cycle.

2.2. Reliability and Product Life Cycle (PLC)

To understand the product behavior in the market, it is important for the manufacturers to have a product life cycle model that can visualize it. The product life cycle (PLC) is the concept model that describes behavior of sales volume and profit
margin of a product over time (Figure 2.2.1.) (Webster, 1984). The purpose of the PLC model is to help the manufacturers to set up, to adapt, or to adjust the related strategy that uses the PLC model as a baseline. The next section describes the phases of the PLC.

### 2.2.1. Product Life Cycle (PLC)

As mentioned in section 2.1.3., the customer complaints correlate to reliability problems. Even though the customer can complain after using the product, the root cause can occur in any phase of the product life cycle. This indicates that the product life cycle will not only have an impact on product reliability but also on other business measures as well, such as customer satisfaction, profit, and product image (Levin & Kalal, 2003). In general, the product life cycle begins with the product development phase and ends with the declining phase. There are some varieties of phases in the product life cycle (Webster, 1984; Ireson & Coombs, 1988; Handscombe, 1989; Kotler & Armstrong, 1991; Levin & Kalal, 2003). The PLC model is defined under an assumption that products are sold. For simplicity, this thesis will adopt the product life cycle phases by Kotler and Armstrong (1991). Kotler and Armstrong (1991) divide the product life cycle into five phases. They are the Product Development (PD) phase, Introduction phase, Growth phase, Maturity phase, and Decline phase as shown in figure 2.2.1.

![Product Life Cycle Model](image)

**Figure 2.2.1. Product Life Cycle Model (adapted from Kotler & Armstrong, 1991)**

1. **Product Development**
   
The phase in which the manufacturer develops a new product that begins with a new idea. During the PD phase sales are zero and the investment costs start to rise.

2. **Introduction**
   
The phase in which the product is first introduced on the market. This is a period with slow sales growth. This phase contributes no profit because of high costs during product introduction. Very few competitors exist in this phase.
3. Growth
The phase in which both market acceptance and profits are increasing. There are many competitors entering the market and their numbers keep increasing.

4. Maturity
The phase in which sales growth is slowing down because the product has achieved acceptance by most potential buyers. The number of competitors reaches a maximum and starts to decline.

5. Decline
The phase in which sales fall off and profits is drop. Only a few surviving competitors exist in this phase.

Figure 2.2.1. shows that the product development process (PDP) is positioned at the front of the PLC model. A product development process is the sequence of steps or activities which an enterprise employs to conceive, design, and commercialize a product (Ulrich & Eppinger, 2000). Because of its position, the PDP has an advantage of preventing the reliability problems before products reach to customers. Many sources point out that the PLC is getting shorter for many, perhaps all, products and services (Rosenau & Moran, 1993; Mi nderhoud, 1999; Brombacher et al., 2005). Therefore, to gain a longer commercial time of the product within a short PLC, manufacturers must reduce their PDP time to the optimum level. However, within a short PDP manufacturers are also confronted with other business pressures. Consequently, in a short PDP, the manufacturers face risks of making reliability problems especially when the PDP is managed improperly. This topic is discussed in more detail in section 2.2.3. The next section further describes the trends affecting the PLC.

2.2.2. Trends Affecting Product Life Cycle

This section describes, in general, the influence of the conflicting business pressures to the PLC and PDP. The business pressures will be further discussed in chapter 3 of this thesis. Sander and Brombacher (2000) conclude that manufacturers of high-volume consumer products are confronted with the following situation:

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

In addition, the manufacturers also have to face the reality of product competition; an enormous price erosion. As a consequence, to stay in the business, the manufacturers have to deal with the situation. Therefore, to compete, the manufacturers have to deliver their new innovative products to the market at a higher rate, reasonable price, and good product quality and reliability. However, the manufacturers must also prepare for the following consequences:

1. Possible immature products delivered to the market.
2. No time to use customer information as feedback in new product generation.
3. Learning time is becoming short.
4. No time to wait for new technology or concept maturity
In short, the situation requires the manufacturers to face the reality that everything they make has to be done within a short time frame. Basically, the idea of delivering a new innovative product in a short time is to gain business benefits. However, it also brings the threat of potentially negative effects. The next section presents these effects.

2.2.3. Effects of Shorter Product Life Cycle

There are various reasons to shorten the PLC as pointed out by Rosenau and Moran (1993), Smith and Reinertsen (1995), Minderhoud (1999), and Brombacher et al. (2005). Shortening the PLC means shortening of the PDP. The advantages of shortening PDP are to achieve fast product introduction to the market and to gain business benefits. Smith and Reinertsen (1995) define the benefits of early product introduction. These include the following:

1. **Extended sales life**
   - If a product is introduced earlier, it seldom becomes obsolete any sooner. It also gains more customers, who maintain their loyalty due to the cost of switching to other products. Consequently, the early introduction develops momentum that not only carries the product’s sales higher but also further into the future.

2. **Increased market share**
   - The first product to market has a 100 percent share of the market in the beginning. The earlier a product appears the better are its prospects for obtaining and retaining a large share of the market.

3. **Higher profit margin**
   - If a new product appears before there is competition, then the company will enjoy more pricing freedom, making higher margins possible.

Even though these advantages are important for the business, this thesis will not focus on them. However, a short PDP also has disadvantages such as reliability problems that a manufacturer must seriously consider. Therefore, instead of focusing on the advantages, this thesis will focus on the disadvantages, namely the reliability problems. In practice, the situation can be illustrated as follows. Within a short PDP, the manufacturer must deal with time-to-market and other business pressures such as product complexity, product quality and reliability, and price erosion. These pressures are caused by the effort to attain competitiveness by delivering an innovative product to the market (Urban & Hauser, 1993; Garcia & Calantone, 2002; Unger, 2003). Therefore, in order to avoid being late in launching the product, the manufacturer can no longer wait until the technology and product development process are completely mature. In this situation, the manufacturer takes risks by launching a new innovative product to the market with limited information of its product reliability problems. Consequently, the manufacturer can unintentionally deliver immature products that have potential reliability problems. In the worst case, if the product is found to be unreliable by the customer, then the manufacturer has two scenarios of actions: corrective and preventive.
Corrective actions
Manufacturers must do their best to remove the reliability problems. The efforts include repair, replacement, or even the recall of the unreliable products.

Preventive actions
Manufacturers must learn from this event and gather available data for future problem prevention.

In any situation, it is suggested to undertake both actions while at the same time seeking new ways to prevent the reliability problems in early PDP. The PDP process is described in the next section.

2.3. Reliability and the Product Development Process

As mentioned in section 2.2.1., generally product development (PD) is a process that transforms an idea and opportunity into a real product. However, the objective of a PDP is not merely to make a product. On top of that, the objective of the PDP is to encourage creativity, resulting in the rapid development of profitable new products for the manufacturer (Rosenau & Moran, 1993). In this thesis, the objective of the PDP is expanded beyond its traditional means to prevent potential reliability problems. Rosenau and Moran (1993) further argue that manufacturers with a formal PD process generally turn an idea into marketable new products more efficiently and faster than those without such a process. Therefore, the manufacturers must customize the PDP based on their needs and culture. In addition, Rudder et al. (2001) suggest that an organization should not be tied to one particular model of the PDP, but organizations should take on board the basic fundamentals of a model and adapt and amend it to a particular situation (Rudder et al., 2001). The generic PDP is described in the following section.

2.3.1. Generic Product Development Process

Commonly, the product development process is divided into several stages. Between stages, there are screening processes that ensure the go/no-go decision, so that only a good product can go to the next step. The purpose of the screening process also is to identify and reduce the risks. Even though PDP models, traditional and innovative, have a similar goal i.e. to respond effectively to the business pressures, in practice they have different PDP stages (Boehm, 1988; Wheelwright & Clark, 1992; Hartley, 1992; Ulrich & Eppinger, 2000; Brombacher, 2000; Dahan, 2001; Cooper, 2002; Unger, 2003). A comparison of a number of available models is summarized in table 2.3.1.

This thesis categorizes in table 2.3.1. the PDP stages into “must-have” stages and “recommended” stages. The “must-have” stages are the stages that are frequently used by several researchers in their PDP model (see table 2.3.1.). The “recommended” stages are less frequent used by several researchers in their PDP model (see table 2.3.1.) but this thesis considers them necessary. The must-have stages are Idea/Concept Generation, Idea/Concept Screening, Concept Development and Testing, Product Development, and Testing. The recommended stages are Business
analysis and Commercialization (Table 2.3.1. and Figure 2.2.1.). Both the must-have and recommended stages are important for the manufacturer to ensure success of the new product development project. Therefore, in the PDP model, both stages are incorporated (Table 2.3.1. and Figure 2.2.1.).

Table 2.3.1. Comparison of Stages in the PDP

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<td>✓</td>
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<tr>
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<td></td>
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<td>✓</td>
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<tr>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<tr>
<td>Packaging development</td>
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<td>✓</td>
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<td>Maintenance</td>
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<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

- **Idea/Concept generation**
  In this stage, the needs of the target market are identified, alternative product concepts are generated and evaluated, product specifications are defined, an economic analysis is done, and the development project is outlined (Ulrich & Eppinger, 2000).

- **Idea/Concept screening**
  In this stage, the product concepts are screened out. Only some of the feasible and the most promising product concepts will enter the next stage. The purpose of this stage is to narrow down the number of concepts quickly and to enhance the concepts. Commonly, concept screening uses a matrix model. The product concepts are weighted against predetermined selection criteria and the results are ranked in the matrix. The selection criteria usually are chosen based on the customer requirements and other important criteria for the manufacturer such as cost and/or risk (Ulrich & Eppinger, 2000).
• Concept Development & Testing
In this stage, one or more promising product concepts are tested to verify that the customer requirements have been met. This stage also verifies the market potential and identifies the potential weaknesses of the product concepts. If weaknesses are discovered, they will be resolved during further development. In addition, if the customer response to the product concepts is poor, then the development of the project may be terminated or some earlier activities may be repeated as necessary (Ulrich & Eppinger, 2000).

• Business Analysis
In this stage, a deep business benefits analysis of the potential product concepts is carried out. The business analysis estimates internal costs, markets potential, and sales forecast. The business analysis also estimates the expected profitability of the potential new product concepts. In this stage, the higher management approval is required, because the commitment from the decision often requires high capital together with extensive utilization of company resources. Commonly, the high capital is used for investment of equipments, facilities, resources, and materials. In this stage, the team from marketing assumes more responsibility than others. The decision made at this stage must conform to company strategic plan and future product development plan. Therefore, the marketing team must regularly consult with higher management for product realization approval of the new product concepts (Bingham & Quigley, 1989).

• Product Development
See Ulrich & Eppinger (2000) for details. This stage can be decomposed into (1) System-level design, and (2) Detail design. In the system-level design stage, the product architecture is defined and the product is decomposed into subsystems and components. This stage also defines the final assembly scheme for product development, while, the detail design stage includes the complete specifications of the geometry, materials, and tolerances of all of the unique parts in the product. This stage also identifies all standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part for manufacture (Ulrich & Eppinger, 2000).

• Testing
This stage involves the construction and evaluation of multiple pre-product development versions of the product. Early (alpha) prototypes are usually built. Alpha prototypes are tested to determine whether or not the product will work as designed and whether or not the product satisfies the key customer requirements. Later (beta) prototypes are usually built. Beta prototypes are extensively evaluated internally and are also typically tested by customers in their own use environment. The goal for the beta prototypes is usually to answer questions about performance and reliability for an identification of engineering changes for the final product (Ulrich & Eppinger, 2000).

• Commercialization
This stage involves a pilot product development of the product. The purpose of this stage is to evaluate the product development process and to identify any remaining flaws on the product. During this stage some products are delivered.
to the intended users to be evaluated and to obtain feedback. If the confidence during the pilot product development is acceptable, the product is ready for the commercial launching.

As mentioned earlier, organizations should consider adapting the PDP based on their existing situation and/or projected future situations and not be tied to one particular model. Even though the PDP model is correctly defined, the risks in the new product development projects that lead to reliability problems are not clearly defined. The next section describes risks and uncertainty in new product development projects.

2.3.2. Risks and Uncertainty

Section 2.3.1. states that to ensure the success of the new product development (NPD) project, the product usually is screened between the phases of the PDP. The screening process is intended to minimize risks. Commonly, NPD projects utilize the same PDP model for any product type. In practice, every NPD project has its own characteristics that depend on the categorization of products, therefore the NPD projects cannot use only one PDP model. One of the reasons some identified PDP models, such as the stage-gate model, spiral model, concurrent model, collaborative model, and others, are introduced is to reduce risks (Boehm, 1988; Hartley, 1992; Wheelwright & Clark, 1992; Cooper, 1993; Dahan & Hauser, 2001; Unger, 2003). This thesis, however, will concentrate on minimizing the potential reliability problems of an NPD project regardless of the PDP model.

A new product can be defined as new when it is new to the company, because the company has never produced this product before although other companies might have already. A new product also can be defined as new to the market or innovative if the product is the first of its kind on the market (Cooper, 1993). Generally, new products can be categorized as follows (Cooper, 1993; Rudder et al., 2001; Trott, 2002):

- **New to the world**
  Products that are the first one and create an entirely new market.

- **New product lines**
  Products that are not new to the market but new to the firm.

- **Additions to existing product lines**
  Products that are new to the firm, but they fit within existing product lines.

- **Improvement and revisions to existing products**
  Not-so-new products, replacement of existing products, or new and improved products.

- **Repositioning**
  Existing products for new applications.

- **Cost reduction**
  New products that are designed to replace existing products in the line. They yield similar benefits and performance at a lower cost.

In fact, the new products inherently contain unknown weaknesses regardless of their type. The weaknesses later can emerge as reliability problems. Therefore, to reduce
potential reliability problems, the unknown weaknesses have to be minimized. In NPD projects, the unknown weaknesses are identified as risk or uncertainty.

Den Ouden et al. (2005) define that risk and uncertainty actually are not similar. Uncertainty is defined as the operational absence of information (useful experience and/or knowledge) from the past. 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” (Den Ouden et al., 2005). Risks events have risk event drivers. A risk event driver is defined as “an enabler that leads to a particular risk event”. In this definition the key distinguishing factors between risk and uncertainty are events and drivers; the risk event and the risk event driver can be identified in the case of a risk situation. In case of an uncertainty, the risk event drivers cannot be identified. Uncertainties at a certain level in a project are often identified as a risk at a higher project level. Therefore uncertainties may appear as risks. This is because uncertainties endanger the success of the project. The way uncertainties should be dealt with, however, differs from the way risks must be dealt with: when an uncertainty is resolved it can become a risk but this is not necessarily the case. For example, when an uncertainty about a new product technology is resolved, it can appear to be no risk in the project. As a consequence, it is a useful strategy to reduce the uncertainties first, then the risks (Lu, 2002). This strategy ensures a proactive action because it can minimize potential risks. Uncertainty, especially in the product development process, can be managed by many methods depending on the location in the PDP. Among other methods, this thesis identifies some of them e.g. Failure Mode Effect Analysis (FMEA), Reliability Quality Matrix (RQM), and High Contrast Consumer Test (HCCT) (Lu, 2002; Den Ouden et al., 2005). There are also available several methods to manage risks in the product development process. Among them are discussed in section 3.4.3. According to Den Ouden et al. (2005), uncertainty can be classified as follows:

- **Market Uncertainty**
  Uncertainty about what the consumers want and what the market looks like. For example, if the market is not mature enough the manufacturer has limited or no knowledge or information about the extreme users. As a result, the manufacturer cannot anticipate the product to withstand the extreme users’ behavior. This situation therefore can create product reliability problems.

- **Technology Uncertainty**
  Uncertainty about the behavior, performance, and quality of product technologies.

- **Industrial Uncertainty**
  Uncertainty about the behavior, performance, and quality of the product development process technology.

Especially for radical innovative products, the term of technical and market uncertainty are defined slightly different (Leifer et al., 2000). Technical uncertainty includes issues related to the completeness and correctness of the underlying scientific knowledge, the technical specification of the product, manufacturing, maintainability, etc. Market uncertainty includes issues related to customer requirements, either existing or latent forms of interaction between the customer and the product, method of sales and distribution, the relationship to competitor’s products, etc. Radical innovation concerns the development of new businesses or product lines, based on
new ideas or technologies or substantial cost reductions that transform the economics of business. Leifer et al. (2000) indicate characteristics of the radical innovative project as follows:

(1) Long-term project
   The duration of the project,
(2) Highly uncertain and unpredictable process
   The uncertainty of the process,
(3) Non-linear process
   The discontinuity of the process,
(4) Stochastic or irregular process
   The priority and key players are always shifting,
(5) Context dependent process
   The dependency of the process with other factors e.g. history, experience, corporate culture, personalities, and informal relation.

In relation to the reliability problems, this thesis will only concentrate on market uncertainty and technology uncertainty (Figure 2.4.4.). So, the industrial uncertainty will not be considered. The next section describes the front-end and back-end of the PDP for a better understanding of the possible root cause of reliability problems.

2.3.3. Front-end and Back-end of Product Development Process

There are no exact clear-cut definitions of front-end and back-end processes in the PDP literature. Ulrich and Eppinger (2000) define the front-end process at the concept phase and back-end process afterwards, whereas, Levin and Kalal (2003) define these processes as proactive and reactive reliability activities. Proactive activities occur in the design phase, and reactive activities occur afterwards. In fact, both models have the same idea and objective. This thesis uses the term front-end process and proactive activities synonymously; it takes place in the design phase, while back-end process takes place afterwards (Figure 2.2.1.). The idea of dividing the PDP into front-end and back-end processes is to give attention and focus to the early processes. Giving attention to the early processes, e.g. concept and design, helps to reduce the development time, and recurrence activities. In essence, the objective is to prevent reliability problems before the design is approved for manufacturing. If the design is already approved for manufacturing, then the reliability problems have a chance of slipping through the product development processes and reaching the customer.

For example, when the reliability problems occur and slip through the product development process but do not reach the customer, the manufacturer has a chance to recall the products with reasonable cost consequences. However, if reliability problems occur after customers use the product, then the manufacturer will face several consequences. The consequences can be that the manufacturer risks customer dissatisfaction, legal warranty claims, and/or lawsuits. Usually, if the reliability problems have potential consequences for customer safety, the manufacturer is urged by law to recall the product from the market (Directive 1999/34/EC; Battell, 2003). In real cases, if the problems can potentially create a bad reputation and damage the company image, then the company will take extreme actions by voluntarily recalling the product from the market and/or applying a product replacement program. In practice, this situation can happen to any company including the established
companies in the field. For example in June 2004, Hewlett-Packard, a global technology company that produces IT infrastructure, personal computers, printers, etc., announced that during routine testing of notebook PCs, the company identified a design flaw in certain notebook memory modules used across the industry that could potentially cause users to experience serious problems with their notebooks. To protect customers, HP instituted a voluntary replacement program for people who had purchased Compaq or HP notebook PCs with the affected memory modules, at no cost to the customer (Business Wire, 2004). A similar example in another industry is Volkswagen recalling 33,000 Passat cars in Europe due to a possible fault with the cars' rear shock absorbers (Source: just-auto.com). In another similar story, in June 2004, Honda Motor Co., Japan's third biggest car manufacturer, said it would recall 70,240 Accord sedans made at its facility in Guangzhou, southern China, to inspect and repair fuel tanks that may be defective (Bloomberg, 2004).

These examples show that companies are willing to take extreme actions by voluntarily recalling the product from the market to protect the customer from being dissatisfied with the product and to secure potential business in the future. Mainly, the cost to settle the problems can be extremely high if manufacturers fail to prevent the problems earlier. In practice, potential reliability problems can be initiated in either front-end or back-end processes. They can be illustrated as follows:

- **Front-end Processes**
  In reference to figure 2.2.1., the process of realizing potential market opportunities as a real product works according to the stages in the PDP. Each stage has its risk and/or uncertainty that can later affect the product. An example is uncertainty that occurs during the translation of customer requirements into product specifications, or from product specifications into detail design. There are many methods, such as Quality Function Deployment (QFD), that can help the process of translating the intangible market input and/or customer requirements into the tangible product specification. In the process, the development teams rely on the tools as well as information available, gathered from previous products, without knowing exactly their degree of uncertainty or risk of product reliability problems. For newly developed innovative products, the development team may have no or little information regarding reliability problems. This can cause the unmanaged uncertainty that happens during the front-end PDP to later create reliability problems. To minimize the uncertainty and risk of reliability problems, the teams will anticipate the reliability problems by predicting them using available knowledge, methods, and tools. This indicates that products, either innovative or evolutionary, risks having reliability problems in the early phase. This is a result of poor (or no) information, tools, and knowledge available or because of other reasons.

- **Back-end Processes**
  Once the design has been approved by management teams, it is ready for real (pilot) product development processes. Product development processes can also contribute to reliability problems, such as weak product development processes, or even immature product development processes. For example, because of time-to-market pressure and to avoid loss in opportunity, manufacturers can take the risk of producing newly developed innovative
products in immature product development processes and/or with an immature technology. Lu (2002) indicates that this problem appears to be due to technology and industrial uncertainties. For example, if a manufacturer must deliver a newly innovative product for a product exhibition, then the manufacturer can take the risk of manufacturing the product in an immature technology and/or product development process. If the manufacturer does not take the risk, then the manufacturer will miss the window of opportunity to be the leader in the market.

Preventing reliability problems at front-end stages of PDP, or any stage before the manufacturing stage, are a proactive approach. This proactive approach can avoid the potential reliability problems at (or after) the stage of the product development process. For this reason, it is important to understand the detectability of reliability problems described in the next section.

2.3.4. Detectability of Reliability Problems

As mentioned earlier, the best way to deal with reliability problems is to prevent the problems before the customer buys the products. Therefore, before defining any strategy, it is necessary to know reliability problems in an early phase of the PDP. Identifying and knowing the reliability problems in an early phase of the PDP can prevent problems and surprises from occurring later on. Even though some of the reliability problems can be detected in early phases of the PDP some others may not be detected. In general, the detection of reliability problems can be categorized as follows:

(1) Reliability problems that cannot be detected during PDP

A soft reliability problem (Customer expectation deficiency, for a definition see section 2.4.2.) already occurs in PDP but can be detected later after customers use the product. For example, consider a new innovative product that is designed to meet customer requirements. The information of the customer requirements were captured prior to the product design process. Meanwhile, during the development process of the product, the real-time requirements of the customer change. In real-time, the customer no longer is satisfied with the previous requirements that they articulated or the customer has more requirements. In reality, instead of incorporating the real-time customer requirements, the development team uses the previous (un-updated) information of the customer requirements in the design process. As a result, the newly-developed product will only be suitable for the previous (un-updated) customer requirements. Consequently, when the new product is delivered to the customer, the customer will consider the product to be unsatisfactory. Although this type of reliability problem originates in the development process, to the knowledge of the author, the problems can hardly be detected during the PDP.

(2) Reliability problems that can be detected during PDP

A hard reliability problem (Specification violation, for a definition see section 2.4.2.) already originates in the PDP process and can be detected during the PDP process. When the technical specifications of a new product have been determined, it is expected that the product will comply with the technical specifications of its design. However, due to technology uncertainty, during PDP
the design specifications may not be realized in the final real product. As a result, the product contains potential reliability problems. Although the problems originate in the PDP, they can potentially be detected during the PDP itself.

2.4. Classifying Reliability Problems

In practice, problems of reliability are broader. Therefore to effectively prevent reliability problems, a model that can represent the broader reliability problems is needed. The model must be able to distinguish the specific reliability problems from the broader reliability problems. From this model, a further strategy to prevent the problems will be derived. Classical approaches, such as bath-tub curve, appear not only to over-simplify the reliability problems but also to lack the capability to distinguish these problems from broader reliability problems (Lu, 2002). This thesis, therefore, is intended to fill this gap. The next section starts with the classical method that is used in modeling reliability problems and ends with presenting the quality-reliability reference model.

2.4.1. Classical Methods

The classical method of modeling reliability problems uses a curve that plots the failure rate $\lambda$ versus the time $t$. The model helps the process of product failure analysis. The most fundamental model is the bathtub curve (Ireson & Coombs, 1988; Lewis, 1996; Brombacher, 2000; Crowe & Feinberg, 2001; Lu, 2002; Petkova, 2003; Levin & Kalal, 2003). The bathtub curve is divided into three regions (1) Infant Mortality, (2) Random Failure, and (3) Systematic Wear-Out. However, it is argued that the bathtub curve model has over-simplified the product failure (Lu, 2002). Therefore, a new model was introduced to replace the curve. It is called the four-phase rollercoaster model (Wong, 1988; Brombacher, 2000; Lu, 2002; Petkova, 2003). The four-phase rollercoaster model is divided into four regions (Figure 2.4.1.):

![Figure 2.4.1. Four-phase rollercoaster model (Wong, 1988)](image)

(1) Hidden 0-hour
Sub-populations of products not meeting with customer requirements at $t=0$. The time delay between the moment of occurrence of a failure and the moment of observation/reporting of the failure determines the shape of the curve. Reasons for failures at $t=0$ can be products outside specification (failed products) that reach the customer, or products inside the supplier specification...
but unacceptable to the customer either due to an incomplete specification or a different perception of the product by the customer.

(2) Early wear-out
Sub-populations of products operating according to specifications but showing deviating behavior with respect to degradation, either due to product tolerances and/or tolerances in customer use. This leads to a situation where such a sub-population of products will be reported to be defective far earlier than the main population.

(3) Random failure
Defects, induced by random events, either internally in the product or externally from customer use or other external influences.

(4) Systematic wear-out.
Defects initiated by failure mechanisms in products that lead to systematic degradation of the main population as a function of time and/or product use.

Both the bathtub-curve and four-phase rollercoaster model consider reliability problems from the perspective of product physical failure. Generally, the classical models classify reliability problems into time dependent and time independent problems. Time independent problems occur immediately after the product is used by the customer e.g. an early failure problem, or problems that happen even before customer uses the product, e.g. dead-on-arrival. This thesis will focus on time-independent failure in class 1 and/or class 2 failures, because for manufacturers the first phase of product use is the most important. Time dependent problems take place a certain time after the customer has been using the product. Instead of using the traditional approach, this thesis will approach reliability problems differently, using a quality and reliability reference model. Before presenting the model, the following section presents a second method of categorizing the reliability problems.

2.4.2. Hard and Soft Reliability Problems

In recent research, Brombacher et al. (2005) categorize reliability problems into (1) Hard reliability problems, and (2) Soft reliability problems. They use the following definitions:

(1) Hard reliability problems (Specification violation)
A situation where a product is not able to meet the explicit technical product specifications.

(2) Soft reliability problems (Customer expectation deficiencies)
A situation where, in spite of meeting with the explicit product specifications, a customer explicitly complains about the lack of functionality of the product.

This definition will be adopted in the remainder of this thesis to classify reliability problems. Even though the classification of reliability problems is clear, the root cause of the problems is not yet clear. The root cause of the reliability problems can happen at any point in the product life cycle. However, the problems only results in complaints after customer use of the product. Therefore, an understanding of the true
nature of reliability problems is very important to establish the root cause analysis strategy. If the understanding of the problems is wrong, then the detection of reliability problems and their root cause also are wrong. As a result, preventing the recurrence of the problems becomes difficult. This research will further decompose hard reliability problems into time dependent and time independent hard reliability problems. Time dependent hard reliability problems are the hard reliability problems situated at phase 3 and/or 4 of the four-phase rollercoaster model. Time independent hard reliability problems are the hard reliability problems situated in class 1 and/or class 2 failures of the four-phase rollercoaster model. Basically, class 1 and/or class 2 failures are also time dependent problems that occur in a small amount of time. Therefore, the effect of time can be neglected or it is called time independent hard reliability problems only. The focus in this thesis will especially be given to time independent hard reliability problems, widely known as early failure problems. The next section presents the Quality and Reliability (Q&R) reference model.

2.4.3. The Quality and Reliability (Q&R) Reference Model

This thesis classifies reliability problems using a three-dimensional model that covers time, statistics, and specifications. The model is called the quality and reliability reference model (Brombacher et al., 2005). Brombacher et al. (2005) define the model of wide-range reliability problems in three important different dimensions:

- Different failure classes (physical or functional failures), located on the specifications axis.
- The relevance of statistics (failures happening only in certain sub-groups of products or in all products).
- The influence of time (random failure or failures due to accumulation of time or customer use of a product).

Using this model (Figure 2.4.3.), it is possible to describe the reliability problems with the factors of time, statistics, and specifications. Time covers the period of product usage by customers. Statistics from field data cover groups of customers that use the product. Specifications cover technical/hard specifications to soft specifications. Therefore, a broad range of reliability problems can be presented by the combination
of these factors (Table 2.4.3.). The next section discusses the specific adoption of the Q&R reference model for this thesis.

Table 2.4.3. Different Types of Reliability Problems (Brombacher et al., 2005)

<table>
<thead>
<tr>
<th>Description</th>
<th>Time dependency</th>
<th>Statistics</th>
<th>Failure class</th>
<th>Customer perspective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal functionality (Nominal) functional drift</td>
<td>No</td>
<td>No</td>
<td>Soft</td>
<td>Certain functions in the product do not work</td>
</tr>
<tr>
<td>Functional yield</td>
<td>Yes</td>
<td>No</td>
<td>Soft</td>
<td>After a while the product is no longer able to function</td>
</tr>
<tr>
<td>Long term functional yield</td>
<td>Yes</td>
<td>Yes</td>
<td>Soft</td>
<td>Some of the products do not work</td>
</tr>
<tr>
<td>Nominal rated (over-) stress</td>
<td>No</td>
<td>No</td>
<td>Hard</td>
<td>The product is defective-on-arrival (DOA)</td>
</tr>
<tr>
<td>Nominal hard degradation</td>
<td>Yes</td>
<td>No</td>
<td>Hard</td>
<td>After a while the product fails</td>
</tr>
<tr>
<td>0-hour failure hard failure probability</td>
<td>No</td>
<td>Yes</td>
<td>Hard</td>
<td>Some of the products are defective on arrival (DOA)</td>
</tr>
<tr>
<td>Long term hard failure probability</td>
<td>Yes</td>
<td>Yes</td>
<td>Hard</td>
<td>After a while some of the products fail</td>
</tr>
</tbody>
</table>

To be focussed on this research:

2.4.4. Adoption of the Quality and Reliability (Q&R) Reference Model

Since this thesis will only concentrate on the early failures (time independent) hard reliability problems, this thesis will only focus on the side at t=0. This plane is called plane I (Figure 2.4.4.). Plane I consists of four sides numbered 1 to 4. Problems classified in this plane may be related to specification aspects and to statistical aspects. The focus of this thesis is on side 2, where the statistics are expected to relate to aspects relevant to some customers, but not to all customers. In terms of specification, side 2 focuses on hard specifications (explicit specifications) to soft specifications (implicit specifications) (Table 2.4.3.). Failures located on side 2 are caused by extreme products, extreme users, or both. Failures caused by extreme products are related to hard specifications. Failures caused by extreme users are related to soft specifications (Figure 2.4.4. and Figure 2.4.3.).

Figure 2.4.4. Focus of this Thesis in relation to the Reference Model
An extreme user is a user who is using a product in an unusual or extreme manner. Extreme use does not automatically relate to misuse, for example someone who solves a problem by kicking the product is misusing it. There is, however, also a group of users which is defined as extreme users. Extreme users relate to the uncertainty in the market, the fitness between what extreme customers really want and what the product can achieve (see section 2.3.2.). Innovative products have partly unknown specifications. Users who use products outside technical specifications but inside customer expectations are extreme users. Extreme products are the products that are manufactured beyond product design specifications. Some extreme products appear due to uncertainty in technology, such as when a product is manufactured using an immature technology (see section 2.3.2.).

2.5. Reliability explained using the Stressor Susceptibility Concept

Section 2.4.2. defines that reliability problems are classified into hard and soft. Moreover, to limit the scope of the research, this thesis will focus only on hard reliability problems or sometimes also called hard failures. According to the definition in section 2.4.2., a hard reliability problem is a situation where a product is not able to meet the explicit technical product specifications. The processes that lead to hard reliability problems are called failure mechanisms. A failure mechanism, on a product or component, is caused by stress factors (stressors) and susceptibility for stressors. A stressor is defined as a physical stress influencing the quality and reliability of a product. Susceptibility is defined as the probability measure that the product will fail after a certain time under a given set of stressors. Typically there are three (basic) types of stressors (1) electrical stressors, (2) thermal stressors, and (3) mechanical stressors. These stressors are also called traditional stressors. The electrical stressor is a stressor that relates to electrical behavior of the product. The thermal stressor is a stressor that relates to thermal behavior of the product. The mechanical stressor is a stressor that relates to mechanical environment of the product (Brombacher, 1992). This research has also observed additional stressors that influence product failure such as environment, chemical, sounds, magnetism, and user. They are also called non-traditional stressors. The environment stressor is a stressor that relates to environmental factors such as humidity. The chemical stressor is a stressor that relates to the chemical environment such as corrosive substances. The user stressor is a stressor that relates to the user. The unusual user behavior on a product, for instance extreme behavior, can be classified as a user stressor. These additional stressors have brought noticeable impact on a product failure.

Usually the stressor and susceptibility are presented as probability density functions.

![Figure 2.5. Example Probability of Failure](adopted from Brombacher, 1992)
The stressor and susceptibility probability density can explain how a failure occurs. A failure may occur when stressor probability density function and susceptibility density function overlap (Figure 2.5.). A more detailed discussion can be found in Brombacher (1992). Figure 2.5. is a graph impression intended to show the process of failure creation. Therefore, the graph should not be used as a precise reference for a failure to appear.

2.6. Summary

This chapter defined some important elements of reliability. It includes (1) the types of reliability problems, (2) the reliability problems detection, (3) the model with which to classify the problems, and (4) the uncertainties that cause the problems. In summary, this chapter draws the following important points from them:

- This thesis will use the term of reliability and customer requirements based on the new definition in section 2.1.4.
- This thesis only deals with reliability problems, violation of part or all of the customer requirements, resulting in customer complaint.
- This thesis splits reliability problems into hard and soft reliability problems.
- This thesis will only focus on time independent (early failure) reliability problems, class 1 and/or class 2 failures of the four-phase rollercoaster model.
- This thesis will look at the problems and/or the root cause at PDP (not after PDP) both in front-end and back-end.
- This thesis will look at the problems in relation to the uncertainty due to technology and the market.

These elements form a bridge to the next chapter. The next chapter will be initiated with business pressures that have a causal relationship with the reliability problems. It will end with the research questions that will be addressed in the remainder of this thesis.
This chapter covers reliability problems in relation to topics that are widely known in new product development practices. The topics are product innovation, business pressures, sharing of information, and common causes of reliability problems. This thesis covers the topics because a strategy to handle the reliability problems can be better defined if the relationship between the reliability problems and the topics are well understood. After discussing the topics, this chapter formulates a research objective. Prior defining the research objective, this chapter defines a map to help restrict the problems and to ensure that the research is specific and focused. The map contains the reliability problems, the topics discussed in this chapter, and the issues discussed in the previous chapter. After having the map, a research objective is defined based on the consideration of the area of interest marked in the map. After that the research questions are derived from the research objective. The last section presents the methodology used to answer the research questions.

3.1. Trends in Product Innovation

Innovation is the first topic to be discussed in this chapter. The purpose of this section is to understand innovation and its relation to reliability problems. The topic of innovation is presented here because "innovation" has been used to drive a new product development, but the meaning of innovation itself is unclear. This section begins with a sub-section of understanding the needs for innovation, the definition of innovation, and the last sub-section explains the relation between innovation and the reliability problems.

3.1.1. The Needs for Innovation

Innovation is widely known by the manufacturers because they believe that innovation can sustain the profit. According to Urban and Hauser (1993) to sustain profit, manufacturers must (1) stay ahead among competitors, (2) increase product superiority, and (3) ensure continuity. For example, to increase product superiority manufacturers should meet the criteria of unique feature(s), more functionalities, meeting customer requirements, and acceptable price/performance (Urban & Hauser, 1993). It is important to note that more "functionalities" are not always adding more satisfaction to the customers than "ease-of-use design". These criteria are also known as business pressures (see section 3.2.). Therefore, to meet the business pressures manufacturers must make innovation on their products. The simple illustration of
innovation is about making things differently (different product or different technology).

Innovation is also used as a strategy to achieve competitive positioning by manufacturers. Niebling and Christie (1991) defined that innovation is one among other methods used to counter-attack the opponents. The counter-attack is part of the defensive approach used by the manufacturers. In the counter attack, innovation is considered as the most successful method. Even though innovation commonly requires high spending in R&D, innovation also gives promising rewards to the manufacturers. Usually those that have a good innovation record are the established market leaders. One of the reasons is because they have strong financial backing.

Considering the importance of innovation for the business, the manufacturers invest and allocate their resources and capability to exploit innovation as much as felt appropriate.

3.1.2. Terminology of Innovation

Many researchers argued on the terminology of innovation that leads to several ways to say the similar thing. Often innovation is defined as “radical”, “really-new”, and “discontinuous”, also innovation is defined as “breakthrough”, “revolutionary”, “game changing”, and “boundary expanding” (Veryzer, 1998; Garcia & Calantone, 2002). To avoid confusion and wrong perception, a clear definition of innovation is needed. For example, if innovation is defined as the degree of “newness” on the product, then the “newness” can be interpreted as new to the world, new to the market, and new to the manufacturer. Therefore, Garcia and Calantone (2002) defined innovation as an iterative process initiated by the perception of a new market and/or new service opportunity for a technology-based invention, which leads to development, manufacturing, and marketing tasks striving for the commercial success of the invention. McDermott and O’Connor (2002) defined innovation as a new technology or combination of technologies that offer worthwhile benefits. Commonly, the terminology ‘innovativeness’ is used as a measure of the degree of ‘newness’. ‘Highly innovative’ products, for example, are seen as products having a high degree of newness.

In this thesis the terminology of innovation by Geudens et al. (2005) is used. The "innovation" on this definition is restricted for "product innovation". Geudens et al. (2005) divide innovation into internal and external innovation. Internal innovation is manufacturing practices (technology, concept, system, work procedures, etc.) that are new to the company. The product developed on this manufacturing practice may contain no newness (old technology). External innovation is a process that brings newness (new functionality) into the product. The newness can be due to new technology. The product can be developed either by new or old manufacturing method (not new to the manufacturer) (Geudens et al., 2005).

3.1.3. Relation of Innovation to Reliability

Even though the introduction of new innovative products into the market is increasing, the acceptability of the products by the customers is not always increasing.
Some customers can easily accept innovation in a new product and purchase it, but some others are waiting a certain time before purchasing the product. The customers usually need time to make sure that the new product performance is good (no reliability problems). The acceptability of a new product by customers is indicated by continuous purchase of the new product by customers. This is known as adoption of innovation, therefore a one-time purchase or trial purchase of a new product is not an adoption of innovation (Onkvisit & Shaw, 1989).

Onkvisit and Shaw (1989) distinguish four types of customers based on the adoption time of a new innovative product. They are (1) innovators; 2.5%, (2) early adopters; 13.5%, (3) early majority; 34%, (4) late majority; 34%, (5) laggards; 16%. The percentage presented here is based on the total customer base. (1) Innovators are the customers who purchase a new innovative product the first time. Even though they are the earliest buyers, usually they will buy a new product after they are convinced of the product’s value. They are less likely to try new products if the products merely present minor changes. Usually innovators are socially mobile, financially privileged, cosmopolitan, and more likely to travel. (2) Early adopters are highly respected. They usually have high income with slightly above-average education levels. It is not uncommon for early adopters to be organizational leaders or to come from the professional and managerial ranks. Before making a purchase decision, they have the benefit to observe and to consult with innovators. (3) Early majority is deliberate. They consider a new product only after gaining their peers’ acceptance. They depend more on informal or personal sources of information in their attempt to minimize the chance of making an incorrect purchase decision. (4) Late majority is known as skeptical. They usually adopt a new product only after being strongly pressured by their peers or being shown the advantage of the innovation over other products. They will only adopt a product if they can accept that the innovation is superior to existing products. (5) Laggards are considered traditional. They normally depend on personal sources such as neighbors and friends for information. They tend to be older and have the lowest status and income. However, they are valuable because they tend to be brand loyal, something that innovators are not.

Regardless the reasons behind the process of innovation and the classification of innovation, in fact as mentioned earlier, innovation contains both risks and uncertainties (see section 2.3.2.). The risks and uncertainties are the primary sources of reliability problems especially when they are not properly managed. This thesis considers the reliability problems that occur in innovative products are caused by two possibilities. They are (1) the risk and uncertainty in the PDP, and/or (2) the way products are used by customers.

Generally, the customers that need time before accepting new innovative products have a learning speed that cannot cope with the speed of innovation, or they are unaware of it. One reason that impedes customers to cope with innovation is because innovation can make the product more complex than before with faster speed. Therefore to stay aligned with innovation, customers require faster learning capability and learning speed. As a result, customers will be able to cope with the complexity of the product and with the speed of innovation. Usually, in high speed of innovation, manufacturers have many difficulties such as with risks, uncertainties, and information system that make the performance indicators that they use are lagging (see also section 2.3.2.). Commonly, these difficulties having impact on the product
reliability problems, either initiated by manufacturers or by customers, are related to business pressures. The next section explains relations of the reliability problems and business pressures.

3.2. Effect of Business Pressures on Reliability Problems

There are many business pressures that manufacturers must seriously take into account such as Time, Profitability, Functionality, and Quality (Sander & Brombacher, 2000; Petkova et al., 2000; Brombacher, 2000). This thesis defines business pressures in slightly different category as: (1) Product Complexity, (2) Time-To-Market, Time-To-Profit, (3) Customer Requirements, (4) Price Erosion and Cost reduction, and (5) Globalization. Basically, the business pressures are the adaptation from the business pressures defined by Lu (2002) with the additional of Price Erosion and Cost Reduction. Reasons of adoption from the business pressure defined by Lu (2002) are (1) to align with the up-to-date reference, and (2) to adapt with recent pressures. For example the issues of price erosion and globalization were in the past considered less a problem than today. The relation of these business pressures with reliability problems is discussed in detail in the following section.

3.2.1. Product Complexity

To stay at the top of the innovation race and increase probability to gain major market share, manufacturers frequently release new products with new functionalities into the market to be purchased by customers. Customers reasonably expect, either articulated or unarticulated, that the new functionalities can satisfy their always changing requirements. However, having new functionalities in the products does not always satisfy customers. On the contrary, having no new functionalities can directly dissatisfy customers (Sander & Brombacher, 2000). It is because if a manufacturer is not offering new functionalities, then other competitors always will. As a consequence of adding new functionalities, the new products become more complex, more difficult to make, and more difficult for customers to use. Therefore, in more complex products, it is vital for manufacturers to prepare for possible increment of reliability problems.

The complexity of the products can be best illustrated in the consumer electronic industries. It is not uncommon that in consumer electronic products the increasing complexities of the products have little or even no effect to the price. Drastically, the increasing complexity of the products in consumer electronic industries conflicts with reality of decreasing the cost and decreasing the Time-to-Market. Time-to-Market (TTM) is the time from initiation of the project to successful launch (Urban & Hauser, 1993). Minderhoud and Fraser (2005) illustrated that the today’s evolution slope of the electronic products e.g. a DVD escalates sharply compared to a CD a decade ago. The evolution of the first DVD generation to the latest generation of DVD took less than five years. In contrast, the evolution of the first CD generation to the latest generation of CD took roughly a decade. Minderhoud and Fraser (2005) also illustrated that the slope of price erosion of the electronic products increases drastically in recent years compared to a decade ago. This indicates that the price erosion in recent years is faster compared to a decade ago. The important point from this illustration is that more complex products are developed in shorter time with lower price in recent years.
Even though delivering more innovative and complex products can increase the window of opportunity and create the possibility to dominate the market, in fact, it is not an assurance to be successful. To be the market leader, manufacturers must bring the new innovative products the first one into the market, meaning that manufacturers must deliver the new innovative products in very short time-to-market.

3.2.2. Time-to-Market (TTM), Time-to-Profit (TTP)

TTM is important especially for products with short product life cycle and high innovation. TTM also is called “Cycle Times”, or “Time-to-Profit”. In this thesis the term cycle time will not be used because of a possible misleading perception with the logistical term. Also, the term Time-to-Profit will not be used in the same meaning as TTM, since it is different.

The TTM not only is an important issue for manufacturers but also it is a key success factor for them in the business. As mentioned earlier, manufacturers must deliver their products into the market as early as possible and become the first one. Delay on launching the products means a loss of competitive position or missing the window of opportunity (Urban & Hauser, 1993). Therefore to be successful, manufacturers apply various strategies to reduce their TTM. Urban and Hauser (1993) defined seven programs to shorten TTM (1) get the slack out of the system, (2) use technology to shorten steps, (3) customer input early to prevent redesign, (4) inventory up-front marketing and engineering projects, (5) flexible manufacturing, (6) alliances, (7) skip a step in the process (occasionally). Whereas Brombacher (2000) defined the strategy to shorten TTM as: (1) shortening existing development processes and, (2) sticking rigidly to procedures. This thesis will not focus on the strategy of shortening the TTM. On the contrary, this thesis will focus on the effect of shortening TTM to the product quality & reliability. One approach to shorten TTM is skipping the steps in the process, e.g. part of the product testing activities. Even though the approach can shorten the TTM it risks of reliability problems.

The definition of TTM has its limitation that is merely on saving time with the expectation to make profit by delivering a new product very early into the market. In reality, early delivery of the new product into the market is not a guarantee of reaping the profit earlier. Profit can be achieved if the customers buy the new product in a certain quantity. Therefore in terms of making profit, Time-to-Profit (TTP) terminology is considered more acceptable. The Time-to-Profit is the moment in time, counted from the start of the development of a new product, when the initial investment of putting a new product into the market is recovered (Brombacher, 2000). The Time-to-Profit also can be related to the Time-to-Market. In general, the TTP is the TTM plus time required for profit recovery after a product is delivered into the market (Dt) (see figure 2.2.1.). The time required for profit recovery after a product is delivered into the market (Dt) is always greater than zero because a manufacturer makes an investment during the PDP. Consequently, the manufacturer makes no profit from the sales till after some time the product is delivered into the market. The relation also can be defined using the following equation:

\[ TTP = TTM + Dt, \quad Dt > 0 \]
where:

\[ TTP = \text{Time-to-Profit} \]
\[ TTM = \text{Time-to-Market} \]
\[ Dt = \text{Time needed for profit recovery after a product is delivered into the market} \]

Brombacher (2000) presents an illustration using the example of two manufacturers A and B competing in the similar market. Manufacturer A has an aggressive PDP, although the cost of this PDP maybe higher, will reach the market earlier because there is a little competition. While manufacturer B considers applying a more conservative PDP will reach the market later. At the same market, manufacturer B also must compete with other competitors. With this illustration therefore manufacturer A has the opportunity to sell product with premium price and saturate the sales channels. While manufacturer B will have to sell the product with competitive price in order to achieve some market share. Therefore, time-to-profit for manufacturer A is shorter than manufacturer B is. In the worst case manufacturer B may never reach the time-to-profit. This means TTP requires more than just the strategy of shortening TTM.

Logically, maximizing the profit can be done by minimizing the TTP by shortening the TTM and/or shortening the Dt. However, to sustain the profit, also an additional strategy to ensure customer satisfaction is required e.g. by only delivering a product with excellent quality and reliability to the customer. This additional strategy requires a method that not only ensures meeting product specifications but also to improve or at least maintain product quality and reliability.

### 3.2.3. Increasing Customer Requirements

The definition of customer requirements used in this thesis is described in Section 2.1.2. Understanding the definition of the customer requirements is important because if manufacturers wish to develop a new product that meets the customer requirements, then manufacturers must seek ways to understand the customer requirements and anticipate future customer requirements. To understand the customer requirements sometimes can be difficult because customers are not always able to state the requirements in detail and they do not deliver a complaint. However, they expect manufacturers to understand their requirements. The best way to understand customer requirements is by talking directly to customer before they deliver a complaint. Customer requirements will become clear when manufacturers listen carefully to the customers (Crowe & Feinberg, 2001). For example, if new functionalities in the new products do not match with customer requirements, then customers possibly will not use the new functionalities. However, delivering a new product with fitness to customer requirements is not a guarantee of success. Because of high level of market competition, the customers not only usually have many choices of the products but also have the ability to compare the price and features with other products offered by other manufacturers, meaning that customers’ decision to buy a product will depend on many factors, one of them is price. Because of a high level of market competition for the similar products, nowadays manufacturers and/or seller attract the customers to buy their products by means such as lowering the price. Therefore, the competition initiates product price erosion.
3.2.4. Price Erosion and Cost Reduction

As described earlier, Time-to-Profit is the milestone to start gaining profit from the development of a new product. However, because of price erosion the milestone can slip from the original plan, and the NPD projects possibly cannot achieve time-to-profit. The effect of price erosion also can be explained. If the price of the new product is eroded then the time needed for profit recovery after the product is delivered into the market (Dt) is getting longer. Consequently, TTP is also getting longer or even cannot be achieved if price erosion is progressing beyond control. This situation is different for innovative products and repetitive products. The illustration is shown below:

1. An illustration in innovative products; as the competition increases, new players enter into the same potential market with more aggressive price competition shortly after the originator launch the products. Therefore, the price battle is getting intense especially if the competitors have a similar strong brand image as the originator (Sander & Brombacher, 2000). In this competition, for the originator it is difficult to saturate the market channel and sell the product with premium price. Moreover, the originator must make price adjustments on their product in order to compete with the competitors. This situation can cause the innovator and all players arriving at time-to-profit longer than expected. In the worst case, time-to-profit is not possible to be achieved if price erosion is progressing beyond control.

2. An illustration in repetitive product the situation is slightly different. Manufacturers that have learned and acquired knowledge from the previous generations of products are called product initiators. As product initiators, they will have the opportunity to develop a new generation of improved products in more cost effective processes. As a result, the price of the new generation of improved products can be lower compared to the previous product generation. In this situation, it is difficult for imitators and new comers that have no knowledge of the (previous) products to compete in low price. This situation increases the possibility for the initiator to dominate the market because of low competition. Therefore, Time-to-Profit always can be achieved because of shorter TTM, little competition, high quantity of products can be sold. It is possible only if the initiator has knowledge acquired from previous experience and has learning capability. The learning capability is important for cost reduction especially in repetitive products.

With these illustrations, to achieve Time-to-Profit the cost effective process must be pursued. Manufacturers of either innovative or repetitive products have to seek a strategy to make cost effective products such as by using a globalized product development process.

3.2.5. Globalization

Globalization has different meanings for different people, one thing in common is that globalization involves many nationalities. This thesis will only consider globalization in new product development regardless of the products’ market. Globalization in this thesis means the development of a new product involving many nationalities at different places. This thesis considers the purpose of globalization of new products development similar to what is mentioned by von Stamm (2003) i.e. cutting cost. Von
Stamm (2003) indicated that cutting cost is one among other strategies that companies pursue by using globalization as their strategy.

To make cost effective new products, manufacturers must develop and produce their products in different locations and countries. In today’s product development concept, manufacturing facilities are located in separate places than the mother factory. Usually, the manufacturing facilities are located in low wages countries around the world. The reasons are to reduce the costs involved in the development and product development process. The global product development process also includes global suppliers and outsourcing strategy. However, the globalization also creates a more complex product development process that poses risks not only to TTM, as mentioned earlier, but also to reliability problems.

Globalization has obstacles that increase risk to the development of new product (Von Stamm, 2003). Many researchers suggested that in the global PDP, manufacturers must anticipate risks due to globalization such as communication barriers because of difference geographical location, culture, language, time difference, values, etc. There are also other barriers such as level of education, skill, work habit, laws, wages, infrastructures, etc. that can impact indirectly to the product reliability problems. Therefore, some manufacturers that have a global PDP try to minimize the risk by regularly exchange within the PDP team. The PDP team in one place is assigned to another place to understand the differences and improve the communication; indirectly the goal is to prevent potential reliability problems.

3.2.6. Summarizing the Business Pressures Trends

It is not a surprise that within the context of these business pressures manufacturers often deliver less mature products to the market. Sometimes manufacturers have no time to wait until the technology is completely mature, manufacturers must deliver the new innovative products while simultaneously improving the products. Less mature products usually contain unknown reliability issues. As a result, if the less mature products are delivered to customers, then the customers will perceive reliability problems. Therefore, in the demanding market, manufacturers must on the one hand strive with the business pressures and on the other hand manufacturers must ensure the products contain less reliability problems. It is also possible that manufacturers can deliver mature products in less mature markets. In less mature markets, usually the manufacturers do not precisely know customers. Consequently, expectations from customer are also less understood. If the expectations from customer are less understood, then what is delivered by the products possibly does not match what the customers expect. In this situation, customers perceive the mismatch as the reliability problems.

To prevent reliability problems in the coming products requires good sharing of information of the reliability problems from the previous products. It is not only how fast the information can be shared but also how useful the information is to prevent the recurrence of the problems. The next section elaborates on the importance of information in reliability problem prevention.
3.3. The Importance of Information in Reliability Problems Prevention

As mentioned earlier manufacturers must struggle within the business pressures to deliver a new reliable product. With the strong time-pressure in the development process, a manufacturer has less time available to perform a detailed root-cause analysis on the product. This may affect the people involved in product development. Consequently, they develop products with little information on actual field reliability performance available (Brombacher, 2000). Moreover, the shrinking of product development time can result in inadequate availability of information on product reliability problems.

Due to impact of faster development cycle, decisions related to improvement on the product should be taken in the early phases of product development (Figure 3.3.). To make a good decision it is necessary that the required information especially on product reliability behavior is available. However, when developing a new product, this will not be easy because currently the development team can only obtain information of the reliability behavior from n-2 or earlier products generation (Brombacher, 2000). In contrast, in the past the development team can obtain the same information directly from the previous generation of products. Consequently, when developing a new product, the development team only has little information on reliability behavior of the previous product. This implies that the development team has to develop a new product that is more complex and more reliable with less knowledge on reliability behavior. This situation risks of delivering a new product to the market with potential reliability problems.

3.4. Impact of Some Factors on Reliability

Identifying and finding the root causes of reliability problems is the important element for successfully removing the problems. To guide to the correct identification of the reliability problems requires an understanding of sources that could lead to reliability problems. Some identified primary sources are described in the following section.
3.4.1. Customers and their Behavior

Reliability problems in a new product are partly caused by customers and their behavior. Therefore understanding the customers and their behavior is important for reliability problems prevention. If customers' categorization and their behavior are understood, their relation to the reliability problems also can be exactly identified then formulating a strategy to prevent underlying reliability problems becomes possible.

There are many ways to characterize customers such as by Hackos and Redish (1998). Hackos and Redish (1998) used the term of user to mean the customer. They divided any user population into four groups (1) Novices, (2) Advanced beginners, (3) Competent performers, and (4) Expert performers. According to Barnum (2002), most users will move beyond the novice stage in time, but few will become expert performers. According to Hackos and Redish (1998), understanding the users needs is critical, because products will succeed only if they facilitate users having successful first experiences, and only if they also allow for growth and learning and for a variety of patterns of use. This classification aims to achieve product success by ensuring successful first experiences when using the product through understanding and fulfilling of the users needs.

This thesis will characterize customers to understand their behavior in relation to product reliability problems. Furthermore, this section characterizes them based on their experience and skill level of using a new product. This method of classification is chosen because the experience and skill level of the customers reflects to their behaviors when using the product. The unusual customer behavior, for instance extreme behavior beyond expectation, can cause the product to fail beyond expectation. The groups of customers are (1) Novice Customers, (2) Normal Customers, and (2) Experienced Customers.

(1) Novice Customers
Novice customers are characterized by the very basic capability of using a new product. This type of customers requires a detailed step-by-step guideline when using the first-time new product. Commonly, novice customers will carefully use the new product according to what is stated on the manual. If novice customers have a problem then they will look for help.

(2) Normal Customers
Normal customers are characterized by the basic skill and experience of using a new product. The normal customers have a basic experience in using a new product, and easily read and understand the new product manual. If the normal customers experience a problem then they can solve the problem on their own. The normal customers use the new product in a normal way according to the specification and within the product design requirement.

(3) Experienced Customers
Experience customers are characterized by the outstanding skill and experience of using any new products. The experience customers normally have an advanced understanding of dealing with a new product. They can use the new product even without reading the product manual. They usually test the product capability beyond its technical specification. They often innovate
the way they use the product which may lead to over use the product. If they have problems then they not only know how to solve but also know the weakness of the product.

This classification indicates that a customer may be classified into different groups for different products. For example, a customer may be categorized as experienced when using a video recorder but a novice when using a DVD recorder.

All type of customers can potentially create reliability problems when using a product. Some customers can unintentionally create the reliability problems, but some others can create reliability problems because of their high degree of innovativeness in using the product.

This thesis also classifies the product usage into three groups (1) Normal Usage, (2) Professional Usage, and (3) Extreme Usage. The classification is based on the utilization behavior of a product.

1) Normal Usage
Normal usage indicates that a customer will use a product according to what the product is designed for. For example, a CD writer that is used by the customer as needed for private or home application.

2) Professional Usage
Professional usage indicates that a customer will use a product for commercial use. The commercial use can be indicated by the frequent use of the product. For example, the CD writer is used in the normal office application to regularly back up data.

3) Extreme Usage
Extreme usage indicates that a customer will use a product beyond the normal way. The product is operated not only beyond the recommendation of practice but also beyond its design requirement. For example, if the CD writer is used in illegal business for continuous copying and/or pirating a CD.

This categorization is presented in table 3.4.1. From table 3.4.1., this thesis only interest to explore the reliability problems related to extreme product usage. The reason is that the focus of this research is on hard reliability problems with aspects relevant to customers (see also section 2.4.4.).

Table 3.4.1. Relation of Group of Customer and Product Usage

<table>
<thead>
<tr>
<th>Product Usage</th>
<th>Group of Customer</th>
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<tbody>
<tr>
<td></td>
<td>Novice</td>
</tr>
<tr>
<td>Normal</td>
<td></td>
</tr>
<tr>
<td>Professional</td>
<td></td>
</tr>
<tr>
<td>Extreme</td>
<td></td>
</tr>
</tbody>
</table>

34
As mentioned earlier (see section 2.3.4.), the reliability problems also can be initiated in any point during the PDP. Furthermore, section 2.3.4. indicates that although the reliability problems are already initiated in the PDP, some of them cannot be detected during the PDP itself. In the PDP, all products will have to go through the manufacturing. Although this thesis focuses its strategy of preventing reliability problems in the front-end process, the manufacturing cannot simply be disregarded because of its position in the back-end process (see section 2.3.3.). No matter how good the front-end process, the product development process contains risk of creating reliability problems in the product. The reliability problems can happen in a weak condition of the product development process, such as due to immature product development process. For example, a new innovative product that is developed in an immature technology and manufactured in immature product development process risks of having reliability problems. The meaning of immature product development process is broader than merely mismatch between available manufacturing technology and required technology to produce a product. It covers all possible weaknesses that lead to inability of the product development process to produce a product with minimum risk of reliability problems.

Many tools have been developed that aim to control the product development process so that the risk of reliability problems can be minimized. The available tools in quality management such as the traditional quality control tools and Statistical Process Control (SPC) are developed on the base of statistical quality control (Bakerjian, 1993; Kimber et al., 1997). They commonly assume that variations in the material, the product and the product development process are the root cause of the reliability problems. These tools, together with improvements made in manufacturing techniques, aim to minimize the variations by controlling the process stability both from the suppliers to the manufacturer. Besides these tools, the quality management systems methods and techniques are also used to ensure the final products have minimum risk of reliability problems. The widely known six-sigma method has been introduced with part of its purposes to improve product quality which is to minimize the reliability problems. The six-sigma method utilizes the best available tools in a structured way to ensure that the final products contain minimal reliability problems (Creveling et al., 2003). In addition to these methods in today’s management practice most established companies also have developed and applied a tailored made self-assessment tool to assess and measure the manufacturing capability and to stimulate the improvement to the higher manufacturing standard. This tool provides a structured, benchmark process for improvement. The benchmarking can be against a company’s previous accomplishments, or against other companies (Bakerjian, 1993).

This thesis, however, focuses not on preventing reliability problems in the product development process by means of controlling the process. On the contrary, this thesis intends to learn from reliability problems on products that slip from the tight control of a product development process. For example, products that are classified as rejected products or will be serviced products. This thesis considers that these products can be used as a possible source to gather information on reliability problems. The information gathered from the products is useful for a test strategy development to prevent the problems in earlier phases of the PDP.
3.4.3. Design Process

As mentioned earlier, the reliability problems can arise at any point in the PDP, such as in the design process due to weak design or other reasons. For example, in the design process, engineers usually take into account any possible weaknesses in the product and incorporate the solution during the design phase. The information on possible weaknesses is captured from the experience of the previous product generation or from the simulation of the design. If design engineers have no information of the product weaknesses then the engineers will not make any adjustment or modification in the design of the product. Consequently, the design of the product risks of reliability problems. However, if design engineers have little information of product weaknesses then they are still able to make compromises on the product to avoid the potential risks.

Generally, the goal of designing a product is to meet the customer requirements with full consideration of the business pressures (see section 2.1.2.). If there is a gap between the design (plan, process, or prototypes) with the customer requirements and the business pressures then the product risks of reliability problems (Clark & Wheelwright, 1993). To minimize a potential gap and to ensure the good design, manufacturers usually use a structured approach in their design process. Among other approaches, Clark and Wheelwright (1993) indicated two approaches that can be used in the design process as (1) Quality Function Deployment, and (2) Design For Manufacturability (DFM).

(1) Quality Function Deployment (QFD)

QFD is a method used to identify critical customer requirements. QFD also helps to make a link between customer requirements and design parameters. In the process, QFD uses matrices to organize information. According to Clark and Wheelwright (1993), QFD helps marketer and design engineer to find answers for the following issues.

(a) Customer requirements that are critical for the customers
(b) Important design parameters that relate to the customer requirements
(c) The target of the design parameters in the new design

(2) Design For Manufacturability (DFM)

DFM is needed to bring the issues of manufacturability earlier into the design process. According to Clark and Wheelwright (1993), DFM consist of two methods (a) Design rules, and (b) Design for producibility

(a) Design Rules
The basic idea is to establish a boundary to ensure that the manufacturing process is capable to meet design requirements. The boundary can be practical rules such as “minimize the number of parts”.

(b) Design for Producibility
The DFM method must be able to fulfill the issues of producibility. The common issues related to producibility such as reducing direct labor cost, reducing manufacturing overhead, or improve quality.
There are also other approaches such as the design-for-X (DFX) methodologies, where X stands for the quality dimensions (see Section 2.1.) such as reliability, manufacturability, robustness, etc (Huang, 1996; Ulrich & Eppinger, 2000). This method, according to Huang (1996), also is capable to improve the aspects related to business pressures and customer requirements. The derivatives of DFX that are important for minimizing potential reliability problems include Design For Manufacturability (DFM), Design For Test (DFT), Design For Serviceability (DFS), and Design For Reliability (DFR). From the DFX derivatives this section will only elaborate on the already mentioned DFM and DFR.

In the design process, usually designers know the issues of reliability problems not as good as reliability engineers. Therefore, it is necessary for designers to have guidelines or practical rules that guide them to consider the reliability issues in the design process. This guideline is called design for reliability (DFR) guideline. Basically, the DFR guideline is similar with DFM, or DFT guidelines that are mostly used by manufacturers. The DFR guideline focuses on the product reliability issues. With the DFR guideline, designers can look for alternative designs and make the right decisions on the design process by themselves.

The ultimate goal in the design process is actually to ensure meeting both the customer requirements and the business pressures. In reality, the program to achieve them can be conflicting. For example, logically to ensure minimum reliability problems the design process requires a program to reduce the identified risks. This program consumes time that can delay the launching of the product. Therefore minimizing risk can conflict with the TTM pressure. Many methods are introduced to minimize risk in the design process with minimum conflict with business pressures. Some of them are (1) design-build-test, (2) design FMEA, and (3) identify-communicate-mitigate (Clark & Wheelwright, 1993; Levin & Kalal, 2003).

(1) Design-build-test

Clark and Wheelwright (1993) defined the design-build-test cycle as a problem solving method in the design process. This cycle attempts to improve the design to meet the customer requirements. If a design requires an improvement to meet the customer requirements then it starts with (1) design phase, (2) build phase, and (3) test phase and returns again to another cycle until the solution is achieved. The number of cycles that is required to arrive to the solution depends very much on the useful information gathered on each cycle. The purpose of the design phase is to phrase the problem and establish the goal of the problem solving. The effectiveness of the process depends on the clear objective defined in this phase. This phase also generates possible design alternatives for the solution. In the build phase the design alternatives are transformed into working models. The purpose is to put alternative designs into a form that allows for testing. In the test phase the working models, prototypes, or computer generated-images are tested. The design-build-test cycle takes place continuously until a solution is achieved. The solution is achieved if the design meets customer requirements (Wheelwright & Clark, 1992; Clark & Wheelwright, 1993).
(2) Design FMEA

The design FMEA is a simple straightforward tool that can help designers identify, characterize, and prioritize risks. The output of design FMEA is a list of design issues that require corrective actions (Levin & Kalal, 2003). The issues are prioritized on the basis of severity of each issue. According to Levin and Kalal (2003), some companies apply the 80/20 rules where the top 20% (corrective action issues) represents 80% of the potential problems. Usually, the weakness in the design FMEA lays on the follow up of the issues. Even though the top 20% issues have been resolved, it is not a guarantee that the design is free from reliability problems. It is possible that the reliability problems are not because of the top 20% issues, but because of unknown interaction of the issues in the list.

(3) Identify-communicate-mitigate cycle

Levin and Kalal (2003) defined the identify-communicate-mitigate (ICM) cycle as a risk mitigation method in the design process. The ICM cycle also can be applied in any phase of PDP to identify new risk issues and to follow up the risk mitigation progress from a previous phase.

(a) Investigate the risk
This process includes identifying and documenting all risk issues, no matter how small the risk. The process covers the detail information of risk such as description of the risk, the impact of the risk, the severity of the risk, and other important information.

(b) Communicate the risk
This process communicates all the information regarding the risk defined in the previous step. The purpose is not only to present the risk information but also to agree on the risks issues as well as commitment to resolve the key risk issues.

(c) Mitigate the risk
This process is known as the risk mitigation plan. The risk mitigation plan defines activities that will take place in the next process. The activities are developed to minimize the risk of reliability problems not only for the next step but also for the final product.

According to Levin and Kalal (2003) risk mitigation requires a 180-degree approach. The approach mechanism model consists of (1) reflecting back, (2) risk mitigation, (3) and looking ahead process. The approach works with reference to the phase where ICM is applied. For example in the PD phase especially in the design activity (see section 2.3.1.), the 180-degree approach is started with (1) reflecting back process, the lessons-learned of risk issues from previous phases of PDP are taken into account. The lessons-learned are captured such as from customer feedback, product recalls, or other sources. The risk issues are prioritized with a Pareto chart. The top issues are identified and transferred to the (2) risk mitigation process. In the risk mitigation process the strategy to prevent the top issues is developed. The next is (3) looking ahead process, in this process the possible upcoming risks are anticipated. The objective of the ICM cycle is to resolve the identified risk issues. The reason is if the risk issues are left unresolved in whatever point in the PDP then product introduction...
may be delayed because the issues will surface and require resolution later in the program (Levin & Kalal, 2003).

These two methods are addressing the potential risks that can later emerge as reliability problems. However, the reliability problems are caused not only because of unmanaged risk but also because of unmanaged uncertainty. What is left uncovered by these methods is preventing the reliability problems due to unknown risk or uncertainty. Earlier research by Lu (2002) also covered the topics of handling the uncertainty in Concurrent Fast Product Development Process. Therefore, this thesis intends to fill the gap by introducing a new method to prevent the problems. The method considers the reliability problems because of unknown risk or uncertainty. If possible the method can be used as a substitute to the available methods. The method will be discussed in more detail in the research objective section.

3.4.4. Plan, Do, Check/Study, Action (PDC/SA) Cycle

The acronym of PDC/SA stands for Plan, Do, Check or Study, and Act. Commonly, the PDC/SA cycle is used as a method of continuous improvement that can be broadly applied in many fields. The PDC/SA steps are as follows (Deming, 1993):

Phase 1: Plan
In this phase, the area that requires improvement is analyzed and prioritized. Usually, the improvement will be addressed to the issues that provide big impact for improvement. In addition, this phase determines the possible approaches for improvement and the possible actions.

Phase 2: Do
In this phase, the plan is implemented. In addition, this phase aims to collect information and to document the observations.

Phase 3: Check or Study
In this phase, the action is monitored, measured, analyzed, and studied. This phase measures the level of improvement made and compares it to the target expected from the plan.

Phase 4: Act
In this phase, further action is decided. The possibilities are to continue to a next cycle or to stop the effort. For example, if the results are as expected then the improvement is a success. However, if the results are not as expected then the cycle can be continued. In addition, this phase aims to document the process and to revise the plan whenever necessary.

Therefore, among other methods such as the well known six-sigma approach of Define Measure Analyze Improve Control (DMAIC) (Harry & Schroeder, 2000), the PDC/SA cycle still can be used to minimize risk (see also section 3.4.3.). This thesis will not specifically promote the PDC/SA method or other methods to prevent potential risks for reliability problems. However, this thesis will consider the method as a general guideline. The reason is because the method is not specifically designed to solve the reliability problems. Therefore, the thesis intents to develop a specific
method of testing that will be defined in the research objective. Before going to the research objective, the next chapter presents methods to map the reliability problems.

3.5. Mapping the Reliability Problems

To make this research as effective as possible, the area where the research will focus must be exactly clear. Therefore, a map of the reliability problems is developed. The map defines the location of the reliability problems among other issues related to reliability problems. Before presenting the map, it is important to define the methods that will be used to classify the reliability problems. The methods are described in the following section.

3.5.1. Methods to Classify the Problems

To restrict only to the specific reliability problems, this thesis categories reliability problem based on:

- Product Structure
- Four-phase rollercoaster model
- Business Process
- Product Development Process

Each of them is described in detail on the following section:

3.5.1.1. Classification based on product structure

Generally a product can be decomposed into its hierarchy, the top level is system and the lowest level is material. The decomposition is divided into 8 levels as shown in table 3.5.1.1. The decomposition of the product is always useful for root cause analysis and prevention of the reliability problems. However, in practice, customers only perceive the reliability problems at the whole product (system level). Therefore, when dealing with the reliability problems, it is important to consider the approaches of perceiving the reliability problems at the whole product and preventing the problems by doing detailed root cause analysis at a lower hierarchy level.

<table>
<thead>
<tr>
<th>Level</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>System</td>
</tr>
<tr>
<td>1</td>
<td>Sub-System</td>
</tr>
<tr>
<td>2</td>
<td>Major Assembly</td>
</tr>
<tr>
<td>3</td>
<td>Assembly</td>
</tr>
<tr>
<td>4</td>
<td>Sub-Assembly</td>
</tr>
<tr>
<td>5</td>
<td>Component</td>
</tr>
<tr>
<td>6</td>
<td>Parts</td>
</tr>
<tr>
<td>7</td>
<td>Material</td>
</tr>
</tbody>
</table>
The reliability problems can occur in any level of the product hierarchy. This indicates that the exact location of the reliability problems in the hierarchy must be clear. Without clear location on the hierarchy, the effort to determine the root-cause of the problems and to remove the problems becomes uneasy. The idea of localizing the reliability problems is to avoid any other influence, and to focus only on the specific problem.

3.5.1.2. Classification based on four-phase rollercoaster model

Reliability problems also can be classified based on the phase in the four-phase rollercoaster model (for details see section 2.4.1.). The four-phase rollercoaster model is divided into four regions that each has different characteristics. Therefore, the reliability problems at each phase of the four-phase rollercoaster model are different. As a consequence, the strategy to prevent and remove the problems is different at each region. This thesis will only focus on phase-1, or 2, which is the early failure problem. The common problem in practice that occurs in this region is known as No-Fault-Found (NFF) that will be discussed in chapter 4.

3.5.1.3. Classification based on business processes

Another method of classification is to define reliability problems based on the business process. The reason is that the reliability problems are expected to be different in every business process. Therefore, the strategy to prevent them also is different for every business process. Brombacher et al. (2005) classify business process into type A, B, and C. The A type is a high tech, fast innovation products. The B type is consumer goods (TV, CAR, etc) that have development times between 0.5 to 2 years and product operational life between 3 to 10 years. The C type is professional (manufacturing) systems where the product has more than 2 years development time with more than 10 years product operational life. Each type of business process has different reliability problems. Therefore, in order to overcome the problem, each different business process requires a different strategy. This thesis will only focus on the business type “A” and “B” in class 1 and/or class 2 failures of the four-phase rollercoaster model.

![Figure 3.5.1.3. Problem Relevance in Business Processes](adopted from Brombacher et al., 2005)
Figure 3.5.1.3. visualizes the classification of business process against the four-phase rollercoaster model. Even though failures in some areas of the business process in the figure 3.5.1.3. are still relevant for further research, this thesis will not concentrate on them. The focus of this thesis is marked with the gray area in the figure that is on the early failures of the high tech products and/or consumer goods.

3.5.1.4. Classification based on stage in product development process

As mentioned earlier, reliability problems can occur at any point in the PDP. Because the phases in PDP have their own characteristic, the strategy for solving reliability problems will differ for each phase. This thesis will also classify reliability problems according to the phase at PDP. The focus of this research will be given to the front-end PDP, see section 2.3.3., especially in the design phase and testing phase. The complete area of interest in this research can be seen in the following section.

3.5.2. Map of the Problems

To be specific and to focus, it is important to clearly define the area of interest in this research because there are many possibilities to distinguish the reliability problems. The area of interest is defined according to the classification described in the earlier sections. Before defining the area of interest, firstly a map where the interest will be located must be defined. The map of the problems is defined in a three dimensional map as shown in Figure 3.5.2.

In the figure 3.5.2. the types of reliability problems, hard and soft reliability problems, are located in the x-axis. In the y-axis the classification based on PDP (see section 2.3.1.), business process (see section 3.5.1.3.), and four-phase rollercoaster model (see section 2.4.1.) are located. In the z-axis the primary causes of reliability problems are located.

Figure 3.5.2. Map of the Problems
The product hierarchy is not presented in the map because at the first problem identification, the exact location of the problem is unknown. The exact location of the failure in the product hierarchy is known only after further root-cause-analysis is performed. Furthermore, reliability problems must always be examined starting from the whole product because customers only perceive the product quality and reliability at the whole product level. The customers have no interest in what happens in detail.

3.6. Research Objective

Considering all topics of reliability problems presented in this chapter and in the previous chapter most importantly the business pressures, the broader reliability problems, and the difficulty to prevent the problems, combined with the identified gap and the weaknesses found on the available methods, leads to the conclusion that reliability problems become difficult issues for manufacturers. Therefore, this thesis intends to fill the gap by addressing the following research objective.

Research Objective:

*Development of a new product testing concept that is used for identification and/or elimination of the time-independent hard reliability problems in the early PDP.*

The research objective is considered not specific. Therefore, to make it specific and clear, the research objective will be decomposed into several parts. The parts will be answered gradually through the following research questions.

3.7. Research Questions

The research questions, a form of structured methods, will be used to fulfill the research objective by answering independently parts of the research objective.

**Research Question 1:**

*Do the class 1 and/or class 2 failures, time independent hard NFF problems, in the context of the four-phase roller rollercoaster model exist?*

Research question 1 will address the following part from the research objective: the *time-independent hard reliability problems*. The existence of time-independent hard reliability problems in practice needs to be clarified. Therefore, this research question will ensure whether time-independent hard reliability problems exist or not.

**Research Question 2:**

*Is it possible to identify, and prevent class 1 and 2 hard reliability problems in the early product development process?*

Research question 2 will address the following part from the research objective: Development of a new product testing concept that is used for *identification and/or elimination of the time-independent hard reliability problems* in the early PDP. This research question will show whether the hard reliability problems in early PDP can be identified or not. The answer will ensure that the testing concept is possible to be applied in the early PDP.
By having the answers to all the above research questions, the research objective is fulfilled. The next section presents the method and strategy used to answer each of the research questions.

3.8. Research Methodology

This section will use the available research methods to answer the research questions in paragraph 3.7. Therefore, this research will not stick to only one research method but to use the (combination of) research methods that are effective to answer a research question.

3.8.1. Research Method

In this research, there are three research methods that can be used as follows:

Survey Based Research
This method uses survey as a method to develop understanding and to draw the conclusion. The degree of understanding depends on the quality of the survey or the questionnaire and the integrity of the answers. Usually, to avoid non-integrity and ensuring concentrated attention of those completing the questionnaire, it is made in short, simple, interesting, and focused. Consequently, survey based research can have difficulties capturing issues outside the topics addressed in the questionnaire.

Case Based Research
This method uses cases from many sources to develop understanding and to draw the conclusion. The overall picture of the research can be defined by performing on adequate number of cases. Therefore, if the number of cases is not adequate then the understanding of the problems also is not adequate. To avoid the limitation, it is better to perform more cases than fewer cases.

Action Based Research
This method pursues action (or change) and research (or understanding) at the same time. The understanding can be gained by action, critical reflection, and continuous refined methods, data and interpretation (Altrichter, 2002). The characteristic of the action research is that the members of the research, from industry and university, participate actively during the research process.

The main consideration in the adoption of a research method is the effectiveness to answer a research question. Therefore, this thesis will adopt a research method situational. The following section defines the strategy and steps to answer the research questions.

3.8.2. Strategy and Steps to Answer Research Questions

The basic strategy is to use a method that can answer the research question in the shortest and easiest way without loosing its validity. Therefore, first of all it is important to know the strength of the method and the nature of the research question to be answered.
Research question 1:
_Do the class 1 and/or class 2 failures, time independent hard NFF problems, in the context of the four-phase rollercoaster model exist?_

The possibilities to answer this research question:
1. Looking at the data gathered from industries of their product problems.
2. Using survey to get information directly from the customers of problems they usually encounter.
3. Working together in a new product development team to experience what kind of problems emerge in the PDP.

The used research method; the step:
Case & Survey Base Research; performing both the possibilities 1 and 2.

Research question 2:
_Is it possible to identify, and prevent class 1 and 2 hard reliability problems in the early product development process?_

The possibilities to answer this research question:
1. To identify the problems in the PDP from manufacturers’ data.
2. To develop a new method for problems identification and to apply the method in several industrial cases together with industrial partners.

The used research method; the step:
Action & Case Base Research.

3.8.3. Actions to Answer the Research Questions

The research questions will be structurally answered in the remaining chapters of this thesis. The next chapter, chapter 4, will present a case study of No-Fault-Found (NFF) as faced by manufacturers. This case study will demonstrate the existence of class 1 and/or class 2 failures of the four-phase rollercoaster model in real application. The data of this case study is gathered from industrial partners during some years of operation. This case study, therefore, will answer the research question 1. To answer the research question 2 requires a new test method that will be tested in industrial application. Chapter 5 will specifically discuss the concept development of new test method that will be used to answer research question 2. After that, the concept will be tested in real application by performing several case studies with industrial partners. The result of the case studies will be presented to answer the research question 2.
CHAPTER 4  THE UNKNOWN RELIABILITY PROBLEMS

This chapter specifically explains a class of reliability problems that is commonly known as NFF. One case study that relates to this topic has been performed together with industrial partners. The case study\(^1\) demonstrated not only the presence of class 1 and/or class 2 failures of the four-phase rollercoaster model in practice but also the presence/dominance of NFF in this phase. This chapter also correlates the occurrence of NFF with existing testing techniques because the testing is expected to prevent the reliability problems during PDP. Furthermore, this chapter argues on the drawbacks of the available testing concepts for solving especially NFF problems. The last section presents the outcomes of the case study that are used to answer research question 1.

4.1. Introduction

Even though most of the causes related to customer complaints are known in practice some of them are still unknown. The unsolved reliability problems are identified as No-Fault-Found (NFF). It is unsolved because the manufacturer is unable to reproduce or identify the customer complaint. Brombacher et al. (2005) indicated in figure 4.2. that in the recent years the fraction of NFF has increased faster than a decade ago. Therefore, firstly this chapter intends to demonstrate the presence of NFF in industrial practice. Furthermore, this chapter also presents the result of fact-finding exercises undertaken during the case study that are related to NFF.

It is not easy to find out exactly the causes of NFF. However, the possible causes that lead to NFF may be categorized as:

1. Problems related to customer usage
2. Problems in the process of analysis (organization, system, and method used)
3. Problems in the product
4. Problems unknown (outside the three mentioned above)

Moreover, during a test, if the abnormality can be found in the product but not a cause then the event is called Cause-Not-Found (CNF). However, this chapter will not specifically discuss these possible causes of NFF. As mentioned earlier, this chapter

\(^1\) The case study was performed together with industrial partners with the outcome of 2 master theses and a paper. Thanks to students van den Broek (2001) and Spronken (2002) for their outstanding contributions on this chapter.
only intends to demonstrate the presence of NFF and problems of early failure in the real industrial application.

4.2. What is No-Fault-Found (NFF)?

There are at least eight acronyms, and possibly more, to describe the same phenomena of the unknown reliability problems. They are NFF (No Fault Found), NTF (No Trouble Found), NPF (No Problem Found), NAD (No Apparent Defect), NEOF (No Evidence of Failure), CND (Can Not Duplicate), RTOK (Retest OK), TNI (Trouble Not Identified). These acronyms indicate that manufacturers pay serious attention to the unknown reliability problems.

This thesis defines NFF as any problems in a product that cannot be reproduced during a technical examination. Usually, if the customers find problems, such as bad product functionality, then they have the right within the warranty time to return the product for repair or replacement to the service center that is appointed by the manufacturer. After the product arrives at the service center, the service center technically examines the product according to the standard procedure. Usually, during the examination, the service center is testing the product functionality and also looking for hard reliability problems in the product. Therefore, if the service center finds the functionality is good, or finds no hard reliability problems in the product, then the service center indicates the problems as NFF. On this situation there are several possibilities that lead to NFF:

1. Possibly the product has problems other than hard reliability problems.
2. Possibly the hard reliability problems are not latent, so that they appear during a short time only and after that disappear again, or appear intermittently.
3. Other possibility is that the method of examination is unable to find out the hard reliability problems because the problems are minor and undetectable.

The fraction of NFF is usually between 25% and 50% (Bothe & Bothe, 2000) and sometimes even up to 80% (O’Connor, 2001) of all returned products. Brombacher et al. (2005) presented that within two decades the NFF jumps almost double from previous value to above 50% now (Figure 4.2.).

Figure 4.2. NFF Trend
(adopted from Brombacher et al., 2005)
Commonly, any unknown problems reported by the customers within the warranty time are registered as NFF regardless of the organizations that handle the product examination. However, if causes of the NFF are unknown but the product abnormalities are identified then it is called Cause-Not-Found (CNF). Besides the service center as the main source of information regarding the product failures, if necessary the information can also be gained from other sources such as user survey, customer help desk, dealers, and/or other sources of information.

Manufacturers focus on NFF because NFF is related to the settlement cost. Commonly, among other methods, the manufacturers apply free replacement programs for the returned product (swap) in their warranty policy. Therefore, the consequence of the free replacement program is cost for the manufacturers. Logically, NFF will generate major cost for the manufacturers because NFF dominates the biggest portion of all returned products. Therefore, to reduce cost, the manufacturers must seriously reduce NFF. It is not only for the reason of reducing the current costs but also for securing the future unpredictable costs because of NFF. Further discussion on cost reduction efforts can be found in section 4.3.1.

4.3. A Case Study Related to NFF

This section presents a case study that is performed together with industrial partners. The partners consist of various groups within an established multi-national company. The case study is performed in the segment of high-volume consumer products especially high-end computer accessories. Even though the details of the industrial partners are available to the author, they are undisclosed for ethical reasons. The case study also can be found in van den Broek (2001), Spronken (2002), and Baskoro et al. (2002).

4.3.1. Case Motivation

Commonly, if a customer purchases a product, the customer automatically gets warranty privileges for the product performance for a certain period. The warranty of some products can be up to three years after purchase. During the warranty period customer’s right is secured such as the privilege to get replacement with the same new product if the purchased product is unsatisfactory. Therefore, from the manufacturer's point of view, securing customer satisfaction during the warranty period is an important objective. It is not only for the purpose of securing the manufacturer reputation but also preventing potential loss because of unreliable products. The reason is that if the customers return the product within the warranty period then the manufacturer must cover all settlement cost. This situation can become serious for the manufacturer if more and more customers return the products that they have purchased.

The positive side of product returns is that the manufacturer can learn from the failures, if the failure root cause is known, for further product improvement. The negative side is that the returned products become a waste of time if the manufacturer cannot learn from them. Possibly, this is because the problems are unknown or cannot be found. This is a costly problem because the manufacturer not only spends the
money for the settlement of complaints but also spends time and resources to search failures that finally cannot be found.

Mostly, manufacturers monitor the product return using a metric called Field Call Rate (FCR). Field Call Rate is the percentage of returned products by customers within the warranty period. The FCR is an important indicator for the manufacturers because it relates to cost of non-quality. Generally, the cost of non-quality is defined as a function of cost of repair and FCR. Therefore, FCR has a linear relationship with the cost of non-quality. The higher the FCR, the higher the cost of non-quality. As mentioned before, among all returned products the NFF dominates around 50% and even more. The rest includes Dead on Arrival (DOA) and products that have hard problems. DOA is a situation in which the product is not working directly after the customer purchases it. Therefore, reducing the NFF will significantly reduce the cost of non-quality. Despite the advantages of the role of FCR as an indicator, earlier research by Petkova (2003) indicated that FCR has also disadvantages such as lagging and also lack of capability to find the root cause of the problems. Even though, there are also available indicators such as Fall-Off-Rate that monitor the percentage of products that are rejected during manufacturing. In fact, these indicators cannot prevent the NFF from slipping through PDP and reaching customers. This thesis, as indicated in the research objective, will also provide the capability of early detection of especially hard reliability problems during early PDP. Consequently, this effort will impact on reducing the cost of non-quality by preventing the problems earlier.

Usually when having complaints, customers return the products shortly after they purchase the products. These products are suspected early failure problems. Commonly, the products are tested during the PDP to ensure the conformity with design specifications and to screen out problems. Therefore, if there are early failure problems then the possibilities that cause the early problems are:

1. The testing is not sufficient
2. The (hard) failure is unknown.
3. The transport causes damage in products
4. Customer related

In this chapter, the attention specifically will be given to the unknown failures as indicated by NFF.

4.3.2. Obtaining Information from Data

Data is an important first-hand source of information because data can be used not only to understand the phenomena but also to make a prediction. Data are any facts, numbers, texts that can be processed to information. Therefore, having the correct data gives useful information to be used for defining a strategy to prevent or remove reliability problems. This is basically a sequence of causal relationship processes that leads to knowledge discovery. In the beginning it starts with rough data. The rough data are processed to be useful information. Then the information will generate knowledge as the basis to make the right decision (van Gorp, 2002). In general, to effectively get the useful information from data, the data user must know exactly the objective from obtaining data.
To achieve the objective the data can be extracted from various sources such as (Figure 4.3.2.):

1. **Internal sources**
The data from internal sources can be gained from test reports, and data saved in a memory module of a product such as EPROM (van den Broek, 2001; Spronken, 2002; Petkova, 2003).

2. **External sources**
The data from external sources can be gained from customer return data that is available in service centers (van den Broek, 2001; Spronken, 2002; Petkova, 2003).

In this case study the process of obtaining data is aimed at achieving the following objectives.

1. **General pattern of failures**
The general pattern of failure will show the pattern of failure during some years of operation.

2. **The cause of failure**
The cause of failure, at least the manufacturing week where the failed products have been produced, will be determined by using MISMOP (month in service and month in manufacturing) diagram (see also section 4.3.4.1. for details).

Normally, rough data also contains unnecessary and overly information known as noise. Therefore, it is important to firstly clean data from noise before organizing them into useful information. This thesis will only focus on the useful information obtained from data regardless the techniques used to extract information from data.

**4.3.3. Method of Analysis**

Figure 4.3.3. shows the steps of analysis during the case study. Initially, data is gathered from various internal and external sources. Data from internal sources, such as gathered from EPROM and test reports during the PDP, is graphically presented as the Pareto of failure. Similarly, data of the returned products from external sources is
also graphically presented as the MISMOP diagram. In this case study, data from internal questionnaires and customer tests is not gathered. The reason is that this data is not directly available; it requires further effort to get this data. Furthermore, to gather data from customer tests is considered not efficient in terms of time, and resources. The reason is because data gathered from internal and external sources is already sufficient to get information related to No-Fault-Found and early failure problems.

From the graphical presentation, such as the Pareto of failure and/or MISMOP, the information regarding NFF, the early failure, and the Time-To-Failure can be gained. From this information, this chapter will only focus on NFF and Early Failure. This information appears in the case study result that is discussed in section 4.3.4.

4.3.4. Results

This section presents the result of the case study that has been performed in an innovative consumer product manufacturer over several years of operation. The product is a family of CD writers with various speeds. The results are presented in the following graphical presentations.

4.3.4.1. Graphical presentation

1. Pareto of Failure

Data for the Pareto of failure is gathered from product return data that is obtained from a service center. The service center is a separate organization outside the manufacturer that is specialized for handling product complaints and/or repair. Van den Broek (2001), Spronken (2002), and Petkova (2003) described in detail the process of complaints handling and/or product repair and the information flow in the service center. Normally, the service center receives the order to handle customer complaints and/or product repairs from various manufacturers. This indicates that the manufacturers mostly outsource their product complaints handling tasks to the service center so that they can focus on the core business. To communicate with the manufacturers and other interested parties the service centers use a standard IRIS
The acronym of IRIS stands for International Repair Information Service. IRIS is a unified, simple method that is used to facilitate exchange of repair information across Europe. According to European Committee of Domestic Equipment Manufacturer (CECED), IRIS has become the official repair data-coding standard for consumer electronics in most European countries. IRIS allows after-sales service providers to receive a detailed description of a customer’s complaint. The advantages of using IRIS are (1) warranty reporting becomes easier, and (2) handling of claims becomes faster. IRIS contains series of code for identification of failure symptoms from the returned products. The complete codes consist of condition code, extended condition code, symptom code, flag code, part code number, quantity, part position number, defect code, and repair code (CECED). Usually, they are simplified into condition code (1 digit), extended condition code (3 digit), symptom code (3 digit), defect code (2 digit), and repair code (2 digit). Therefore, in total there are 11 digits in the IRIS coding system.

In practice, the correctness of the given IRIS coding depends on how good the root cause analysis is performed by the service technician. Therefore, the knowledge of product failure analysis from the technician is important because the failure symptom is associated with the given IRIS coding. It is possible if failures on a product are ambiguous then the technician put coding 1X00000000 as component no-fault-found or 0X00000000 as unit no-fault-found. Consequently, if the symptom of failure is unclear then it opens room for misinterpretation to NFF. This indicates that IRIS coding contains some drawbacks. Earlier research by Petkova (2003) explains the drawbacks of IRIS coding. Further discussion of IRIS coding also can be found in Spronken (2002). This chapter, however, only intends to use IRIS coding to show the presence of NFF in practice.

Figure 4.3.4.1. shows the domination of NFF in a product family during three consecutive years. The graph presents the frequency of failures from all products returned in a year. The type of failure in x-axis represents the IRIS-coding. However, this graph intends to present only the frequency of failures that relate to NFF. Therefore, the other types of failures are not exposed in the graph. On this graph, NFF
is divided into component-NFF and unit-NFF. It is ambiguous to differentiate between component-NFF and unit-NFF. What differs between them is only the first digit in IRIS-code. Component-NFF is registered as 1X00000000 and unit-NFF is registered as 0X00000000. The first digit in IRIS-code, the condition code, represents the condition under which a defect occurs. With component-NFF, for the first digit space, condition code, a 1 means “constantly” failure. Whereas, for the unit-NFF, the condition code 0 is unknown because the registered condition code in IRIS-coding is from 1 to 9. However, other codings outside condition code for both unit and component NFF has the same code i.e. *X00000000, which means No Fault Found because the problems simply are unregistered in the IRIS-coding system. It is shown that during year 1999 the percentage of component-NFF is around 20% and unit-NFF is below 5%. One year later, in the year 2000, the component-NFF jumps more than 100% to around 45% and unit-NFF stays constant at below 5%. In the year 2001 the component-NFF is slightly reduced to around 35%, and unit-NFF jumps to around 20%. In the year 2001, other failures that have never been experienced during the past years also emerge. Figure 4.3.4.1. demonstrates that the NFF trend, both component-NFF and unit-NFF, stay high or even increase. The situation of increasing NFF trend indicates that the manufacturer has difficulties to tackle NFF using the existing available methods.

2. MISMOP
MISMOP is a method for presenting the frequency of product failures on the basis of month-in-service versus month-in-production (van den Broek, 2001; Petkova, 2003). The basic idea of MISMOP is to map the distribution of the product failures so that the situation can be examined. For example, for early failure problems the distribution can be predicted spread out in early month-in-service regardless the month-in-production. Using a MISMOP diagram, the correlation of problems in the product to its manufacturing date can be defined. By knowing this relation the manufacturer can figure out the situation on the manufacturing that leads to the problems.

MISMOP can be presented in two time based methods (1) Calendar time, and (2) Real time. Calendar time is time calculated based on the calendar. Therefore, calendar time only indicates the period after the product left the factory until it returns back to the factory. Real time is the operating time of the product. Usually, real time is calculated based on the power-on hours of the product (obtained from the EPROM in the device). MISMOP helps identifying the time-to-failure of the product and the period when the failures occur during manufacturing. The time-to-failure in a MISMOP diagram is presented in terms of calendar time. This is one of the drawbacks because

![MISMOP Diagram](image-url)

Note:
Product return after production = date in – production week

Figure 4.3.4.2. Method of Data Handling
MISMOP is unable to present time-to-failure based on real operating time. Furthermore, to plot a MISMOP diagram some adjustments are required to define the time required by a product to return back to the manufacturer. In practice, if a product is returned to the service center for repair the only data available is the return date to the service center (date-in), the return date to the customer (date-out), and the batch when the product is manufactured (production week) that is available in the product serial number.

Figure 4.3.4.2. shows the method of obtaining month-in-service on the basis of calendar time. Logically, month-in-service is the duration of a product at customer’s hand, regardless whether the customer uses the product or not. For simplification month-in-service is calculated based on the duration of the product usage since the product leaving the factory until the same product returning back to the factory. Logically, this method of calculating month-in-service is not totally correct because it is not clear how long the product has been in the customer’s hand and how long it stays with the distributor (hub). However, because of the limitation of the available data that is only date-in, date-out, and production week. Month-in-service is assumed equal to the period of product return after manufacturing that is date-in minus production week (See Figure 4.3.4.2.). In this calculation the date-out data is not used because the date-out has no direct relationship to month-in-service. Date-out is only an indication of the period of repair process that occurs in the service center. Moreover, date-out can be used to define the frequency of the same product that is returned for services during the warranty period.

Figure 4.3.4.3. plots month-in-service vs. production week (MISMOP) using calendar time of products manufactured during year 2000. Horizontally, the graph shows the estimated usage interval of the product or months-in-service. Vertically, the graph shows production week. Each data point in the graph indicates a returned product.
produced at a certain time and used for a certain time interval. The graph shows that most products are returned to the service center after less than 2 months in the customer’s hand (see horizontal axis). Also, the graph shows that a major part of the returned products were manufactured in the production week 10 of the year 2000 (see vertical axis).

Furthermore, instead of using calendar time, MISMOP can also be plotted using real time data as long as the data is available. Plotting MISMOP using real time data gives a real picture of the failure characteristics in the product. The real time data related to product failure is the user profile data available in the EPROM. EPROM records data of the accumulation of the power-on hours. The power-on is a situation when the power of the product is turned on. Therefore, this is the total operating hours of a product. The real time data from the user profiles can be presented against the production week in 3D MISMOP (Figure 4.3.4.4.). Figure 4.3.4.4. shows the occurrence of early failures from the same variant of the returned products by the customers. The products fail in less than 50 power-on hours.

![Customer Profile of Production Year 2000](image)

Figure 4.3.4.4. 3D MISMOP diagram showing the frequency of returned products as function of power-on time and production week

**4.3.4.2. Information extracted from the graphic**

The important point on this case study is to obtain the information of NFF and early failures. This information is needed not only to answer the research questions but also to be used for further strategy development to prevent and reduce hard reliability problems.

There are three important pieces of information gained from this case study:

1. **No-Fault-Found**
   The case study demonstrates that the NFF graph, presented in Figure 4.3.4.1., corresponds with the NFF graph in Figure 4.2. This figure is the result of a case study that demonstrates the domination of NFF up to the recent years. So far, the figure remains unchanged.

2. **Early Failure Problems**
   Results from the same case study, presented in 2D & 3D MISMOP, show that the failures can be categorized as early failure problems as demonstrated in Figure
4.3.4.3. and Figure 4.3.4.4. The Figure 4.3.4.3., 2D MISMOP plotted based on calendar time, shows that mostly the products are returned to the service center within two months after the products have left the factory. Furthermore, 3D MISMOP in Figure 4.3.4.4., plotted based on real time, shows that the products fail in less than 50 hrs of power-on. In Figure 4.3.4.4. there is also an indication of failures that occur in 200 power-on hrs. Commonly, these failures are created at a certain production week. These failures are not categorized as early failures problem because they occur after some time of usage. These failures are suspected because of seasonal problems in manufacturing. Usually, in a certain production week, manufacturing is loaded more than usual because the company needs to make more products for a peak season and/or to anticipate the coming peak season. This situation can create a low quality in manufacturing that also impacts on the quality of products. Therefore, the products at this production week fail after some time of usage as shown in the Figure 4.3.4.4. Clearly, these two graphs demonstrate the occurrences of early failures in practice.

3. Turbulence in Product Development Process

Figure 4.3.4.3. shows that the frequency of the returned products is mostly related to a particular production week. This indicates that beyond the particular production week there is no significant frequency of products return. Therefore, in this case study, it is argued that reliability problems occur only in the particular production week during the one-year manufacturing plan. However, this chapter will not elaborate further on the reasons of product returns on that particular week. On the contrary, this chapter focuses only on the (type of) reliability problems, regardless in what production week the products are manufactured.

From the above list of information, at least two issues are important for this thesis. They are the No-Fault-Found and the Early Failure Problems. The occurrences of NFF and early failure problems indicate that the programs to screen out the unreliable products during PDP cannot detect the problems. Among other programs that are used by the manufacturer, the testing programs during PDP are the main concern of this thesis. The testing programs that are used by the industrial partner during the case study are discussed in section 4.3.5.

4.3.5. The Testing Programs used by the Industrial Partner

The industrial partner that collaborated during the case study used several testing programs in the product creation phase. In this case study, the product creation phase is simply divided into (1) Planning phase, (2) Realization phase, and (3) Manufacturing phase. Actually, if these phases are further detailed then the phases are comparable with the generic PDP phases as described in section 2.3.1. The testing programs used by the industrial partner are (1) Functional Test, (2) Verification test, (3) Maturity test, and (4) Reliability test. The purpose of functional test is to evaluate the prototype and to conform it to the specification. This test is carried out at the beginning of the PDP. The verification test aims to verify that the design conforms to the specification and to identify problems that can be solved early in the planning phase. The verification test is applied from the beginning of the PDP process up to the realization phase. The maturity test aims to ensure that the product is already mature and capable of achieving its specification as a total integrated system. The maturity test is done between the realization and the manufacturing phases. The last testing
4.3.6. Review of Case Study

In this section, the details of the test programs are not discussed. It is assumed that the programs have been done accordingly. This is a reasonable assumption because high caliber companies, including but not limited to the industrial partner involved in this case study, usually set strict rules to attain and maintain their best practices. Commonly, to maintain high manufacturing standards the company regularly audits the compliance of the practical work with standard operating procedure (SOP) sets for that particular work. If the practical work is found to be non-compliant with SOP, then the company directly issues a change proposal for corrective actions. Therefore, in this case study, the testing programs are reasonably assumed working according to the standard operating procedure and carried out with high engineering standard.

In fact, during the case study, all the returned products as mentioned in the earlier paragraphs have been dominated by NFF during the three consecutive years of operation. This fact indicated that there is a weakness in the existing testing programs. Chapter 5 will discuss the possible weaknesses of the existing testing methods in relation to the reliability problems. Meanwhile, section 4.4. will present the summary of the important findings from this case study in relation to research question 1.

4.4. Summary

This section tries to answer the research question 1 according to the strategy mentioned in section 3.8.2. Research question 1 is defined as follows:

*Do the class 1 and/or class 2 failures, time independent hard NFF problems, in the context of the four-phase rollercoaster model exist?*

According to section 3.8.2. there are several possibilities to answer this research question:

1. Looking at the data gathered from industries on their product problems.
2. Using survey to get information directly from the customers of the problems they usually encounter.
3. Working together in a new product development team to experience what kind of problems that emerge in PDP.

From these options, this research chooses options 1 and 3 because results from these options can represent problems in industrial context. In contrast, this thesis considers results from option 2 may not be sufficient to represent problems in industrial context. The options 1 and 3 are represented by the first case study as presented in this chapter. This case study uses the case based research method.
According to section 4.3.4.2., this case study has demonstrated two important findings that are relevant to answer the first research question. The results are as follows:

- NFF is a real serious problem for the manufacturer as shown from the symptom of failure in the return products. The symptoms of failures are processed using IRIS coding (Figure 4.3.4.1.).

- Early Failure Problems are also real and dominate significantly from the failures reported by service centers. The data is gathered and visualized using MISMOP and plotted both in calendar time and real time (Figure 4.3.4.3.; Figure 4.3.4.4.).

Based on these findings, this chapter has demonstrated the fulfillment of research question 1. The answer from research question 1 is Yes!; the failures categorized as class 1 and/or class 2 failures in the four-phase rollercoaster model can exist in practice.

The next chapter, chapter 5, will focus on the development of requirements for a new test method that will be tested in a real application in order to answer the remaining research questions.
CHAPTER 5  ASSESSMENT OF CURRENT TESTING CONCEPTS

The aim of this chapter is to assess the current testing concepts. However, before presenting the assessment from the current testing concepts, this chapter discusses the criteria for testing that are used in the assessment. The results from the assessment will be used in the development of a new testing concept in chapter 6.

5.1. What is Testing?

This section will present the general discussion of testing concepts. It is important to note that this section is not intended to cover all available testing concepts. In contrast, this section will only present testing concepts that are considered relevant for this thesis. For this reason, this thesis will present a classification of testing concepts in section 5.2.

5.1.1. Introduction

Although there are many objectives for testing, this thesis simplifies them into (1) Marketing oriented test, and (2) Reliability oriented test.

(1) Marketing oriented test

Usually, in marketing, the test purpose is to assess the sale ability of the product to maximize the profit by optimizing product sales. Marketing gives not much attention on the details of problems on a product. In past decades many researchers have broadly discussed test marketing and they argued that the results were ambiguous (Hardin, 1966). In the past, test marketing had been addressed with the purpose to maximize profit, to obtain the market profile, to gather up-to-date trade information, etc. (Ladik, 1960; Hardin, 1966). Nowadays, test marketing is still used with a similar purpose although it is applied on different kinds of products with more sophisticated tools than before (Dahan & Hauser, 2001). The difference between tests in marketing and tests discussed in this chapter is on the test purpose. Tests in this thesis focus on the details of a problem in order to solve and to prevent it. Therefore, this thesis will not deeply discuss marketing oriented tests.

(2) Reliability oriented test

Many tests have been developed to improve the quality of a product. The term quality instead of reliability is used here because, as noted in section 2.1., these
two terms are misleading. It is because formerly the definition of reliability is not as clear and unambiguous as used here. However, the orientation of many tests is actually the reliability-oriented test as known today. Generally, these tests are developed to ensure that the product fulfills customer requirements over time and under stated conditions (see also section 2.1.4.). However, in application each test uses different concepts and approaches. Therefore, it is not surprisingly if there are many names of tests available today in practice.

This thesis will specifically deal with the reliability-oriented test. Moreover, the next section tries to analyze concepts of testing.

5.1.2. Classification of Testing Concepts

Usually, testing is developed with a certain concept. This section presents a classification of testing concepts that can be found in practice.

5.1.2.1. Classification based on test method

- **Statistical oriented test**
  This thesis defines statistical oriented test as a concept of testing using mainly statistical techniques. It uses statistical techniques and tools to interpret data, to draw conclusions, and/or to make predictions. Data can be gathered by mining from customers’ feedback or other sources of data. Commonly, to get significant results, statistical oriented tests require the availability of a large number of samples. Therefore, this concept is considered very late if it is compared to the development time of the new product. Normally, it requires several months to get the field feedback from the new launched products. At the same time, the next generation product is already in the pipeline and ready for launching. Therefore, there is little time available to learn from the field feedback using statistical analysis to make predictions for new product performance (Petkova, 2003). Other drawback is about the cost required to get samples for the test. The large sample sizes are associated with high cost.

- **Engineering oriented test**
  This thesis defines engineering oriented test as a concept of testing using mainly engineering knowledge. The engineering knowledge includes technical knowledge of the working principles and related failure modes of a product. The engineering oriented tests aim to analyze product defects, or at minimum to find the signature of defects. Furthermore, these tests are also aimed to detect and to remove the (sign of) potential defects before the product is fully assembled into a complete product. Therefore, this test requires product knowledge that relates to product failure. The advantages of engineering oriented tests if compared to other concepts are a small sample size requirement and relatively short time consumption in its execution. Time consumption in a test execution includes actual test time and preparation time. Actual test time is time needed during the test execution. Preparation time is time required for test preparation. The disadvantages are about potential unavailability of the product knowledge especially for the first-of-its-kind product and the necessity of vast engineering expertise and experience. Therefore, to successfully perform engineering oriented tests requires good learning capability and knowledge acquisition from every generation of new products (Jager, 2004).
5.1.2.2. Classification based on test purpose

- Analysis test
  Analysis test is aimed at understanding the root causes of the (potential) product problems. Therefore, it requires an understanding of product failure characteristics and physics of failure knowledge. In practice, failure analysis can be done in many ways with various tools such as using computer failure analysis. However, instead of using other concepts/tools this thesis prefers to use product-testing concepts for failure analysis. Basically, the product is tested until it fails followed by root cause failure analysis. Commonly, this can be performed using an engineering oriented test concept because the engineering oriented test is capable of carrying out product failure analysis via testing. However, the drawback of using an engineering analysis test concept is that this test has to be carried out at the backend of the PDP because a product has to be available. For example, engineering analysis test only can be done after the product is completely assembled and leaving the manufacturing or when the customers return a product. Consequently, this class of test concepts will be too late when carried out at the backend of PDP.

- Validation test
  Validation test is aimed at verifying the compliance of the product with its specifications. There are many ways to perform validation tests such as by statistical oriented test and also by engineering oriented test. However in practice, validation test is performed using statistical oriented test concepts both during manufacturing and after manufacturing. Commonly, some product samples are taken from the ongoing manufacturing to be tested. The expectation of performing this test at manufacturing is to find the deviation between the design specification and the realized specification as early as possible. However, there is no guarantee that this testing can find problems in early PDP processes. Consequently, if this testing finds problems after manufacturing or at the backed of the PDP, then it is already too late.

5.2. Description of Testing Concepts

Although there are many testing concepts available, it is important to notice that not all of them will be discussed in this section. This section only considers some of them in order to demonstrate their advantages and disadvantages. Later, the information obtained will be used for the development of a new testing concept.

5.2.1. Prototype Testing (Alpha, Beta, and Gamma test)

Alpha, Beta, and Gamma test are the testing concepts that are commonly used in the prototype testing. Therefore, they are also called prototype testing (Ozer, 1999). Below are the descriptions of them.

**Alpha Test** i.e. Pre-manufacturing product testing to find and eliminate the most obvious design defects or deficiencies, usually in a laboratory setting or in some part of the developing firm’s regular operations, although in some cases it may be done in controlled settings with lead customers (Rosenau et al., 1996).
**Beta Test** is an external test of pre-manufacturing products. The purpose is to test the product for all functions in a breadth of field situations to find those system faults that are more likely to show in actual use than in the firm’s more controlled in-house tests before sale to the general market [PDMA Handbook].

**Gamma Test** is a product use test in which the developers measure the extent to which the item meets the needs of the target customers, solves the problem(s) targeted during development, and leaves the customer satisfied [PDMA Handbook].

5.2.2. Accelerated Testing

Although accelerated testing is commonly used today, it frequently means different things to different people. Commonly, there are two main reasons for performing an accelerated test i.e. life estimation or problem identification (or confirmation) and correction (MIL-HDBK-338B).

a) Accelerated Life Testing
The focus is on estimating the life of an item under “normal” operating conditions, based upon data obtained under much more severe conditions. Therefore, this testing concept can gain time if compared to test in normal conditions. In this case, the failure mechanism is usually well documented and understood; thus, problem identification and correction is of secondary importance.

b) Accelerated Stress Testing
Accelerated Stress Testing is used to identify problems and weaknesses inherent in the design, the parts used, or the manufacturing process so that they can be fixed subsequently. This is done by changes in: the design itself, the parts used, or the manufacturing processes employed. A thorough understanding, or at least a workable knowledge, of the basic failure mechanisms is the focus of attention here, estimation of item life may, or may not, be a concern. Accelerated stress testing has also disadvantages especially if the applied stress is higher than normal condition. Firstly, if the applied stress is higher than normal usage condition then the translation of high stress to normal usage condition can be irrelevant. Secondly, if the applied stress is higher than normal condition then the applied stress can practically trigger irrelevant failure mechanism.

5.2.3. Highly Accelerated Testing

Highly accelerated testing attempts to reduce the time needed to do a test. The approach may be used either for development testing or for screening.

a) Highly Accelerated Life Test (HALT)
HALT, also sometimes referred to as STRIFE (Stress plus Life) testing, is performed during design to find the product weaknesses such as imperfections, design errors, and design marginality of the product. After these design issues are identified, they can be corrected by means of redesign. The HALT process is repeated to verify that the design changes worked and that no new design issues emerge (Levin & Kalal, 2003). Usually, the applied stresses to the product are well beyond normal shipping, storage, and application conditions. Commonly after applying HALT, manufacturers perform a Highly Accelerate Stress Screening (HASS) to screen the products. HASS is performed in the manufacturing stage to confirm that all reliability improvements made in HALT
are maintained. It ensures that no defects are introduced due to variations in the manufacturing process and vendor parts. Therefore, HALT is a development tool and HASS is a screening tool. They are frequently employed in conjunction with one another (MIL-HDBK-338B).

b) Highly Accelerated Temperature and Humidity Stress Test (HAST)
With recent improvements in electronics technology and the speed of the technology, the available accelerated tests may no longer be adequate and efficient for today’s technology. This is true for accelerated tests intended specifically for microelectronics. For example, using classical test methods may take thousand of hours to detect failures in new integrated circuits. In addition, the test may end up without any failures. A test that finishes without finding failures tells us very little. Without failures we lack the knowledge necessary to make product improvements. Therefore the accelerated test conditions must be redesigned accordingly (e.g., utilize higher temperatures) to shorten the length of time required for the test. Therefore, improvement of accelerated tests is needed to make it more efficient and hence more cost effective. This is the background for Highly Accelerated Temperature and Humidity Stress Testing (MIL-HDBK-338B). HAST is an environmental reliability test that includes a combination of several stressors.

5.3. Criteria for Testing Concepts
This section presents three main criteria that will be used to assess the testing concepts. They are efficiency, effectiveness, and position in PDP. Moreover, the testing concepts that are discussed in this section will be analyzed using the criteria in section 5.3.

5.3.1. Efficiency
The term efficiency in this thesis indicates the productivity of testing. For example, if more testing can be performed during an allocated time interval then the testing is said to be more efficient. Therefore, efficiency is also related to the timing and cost. There are two issues related to timing i.e. (1) quick finding of problem root cause, and (2) quick utilizing the result for product improvement. In attempt to find quickly the root cause of a problem, a test concept should be fast in test execution and it also should be fast in the analysis of the result. In attempt to utilize quickly the result of the test for product improvement, the new test concept should fit with the current PDP test program and it should be applied in the early PDP (see also section 5.3.3.). Although there are several considerations for cost of testing, this thesis considers a test is cost effective if it can save time. Therefore, to have optimal efficiency, a subsequent test should not repeat the previous test. This indicates that the test should be successful in one time in order to allow more testing to be carried out at the allocated time. Furthermore, it is useful to define the success criteria early during test preparation. It is because if the success criteria are not clearly defined then misinterpretation of the test success is possible to happen. As a result, if the test success is ambiguous then it is potential to repeat the test that is unnecessary. This is a potential cause of inefficiency because test repetition consumes time. Furthermore, for simplification, this thesis uses the judgment of efficiency based on the sub criteria of (1) requires shorter test time, (2) requires small number of samples for test, and (3) uses large number of stressors with limited experiments (see also table 5.5.1.). Along with sub
criteria (1), the sub criteria (2) and (3) have also impact on the efficiency that is time required to perform the test. Logically, as stated in sub criteria (2), if the test uses small number of samples then potentially the test will be finished faster than when using large number of samples. Also, as stated in sub criteria (3), if the test uses large number of stressors but when it is performed with limited experiments then the time required for the test will be shorter. The advantage of accommodating large number of stressors is to increase the probability to find the failure. However, if using large number of stressors then it is normally associated with longer test time. Therefore, to avoid longer test time, sub-criteria (3) recommend using limited experiments when accommodating large number of stressors. Consequently, if the test can be done faster that can be achieved by fulfilling the sub criteria then the test is efficient. Furthermore, the sub criteria that are used for the judgment of efficiency are applicable for any test regardless the number of stressors.

5.3.2. Effectiveness

The term effectiveness is used in this thesis related to the result of testing. The result of testing can be related to the ability of testing to find an expected failure from the tested product. Generally, there are many classes of failures and any failure can emerge during product testing. Therefore, as indicated earlier, this thesis will only seek to find a specific class of failures and to disregard others. This thesis simplifies the failure that emerges during the testing into (1) primary failure, and (2) secondary failure. The primary failure is the failure that emerges during the test and it is included in the class of early failure hard reliability problems. The secondary failure is the failure that emerges during the test but it is included in different class of failure other than the early failure hard reliability problems. Therefore, this thesis considers the test is effective if the test can find the primary failure or the failure in the class of early failure hard reliability problems.

It is also possible that the testing will not find the primary failure. This situation can be explained from the test coverage. The test coverage is ratio between tested specifications and total specifications. Therefore, if the test covers few specifications then the primary failure possibly may not be found. The reason is if using small test coverage, few specifications are tested, then the stressors applied during the testing is also few. If using few stressors then it is possible that the applied stressors may not be the cause of the primary failure. Consequently, if the stressors are not the cause of the primary failure then it may not be found. Therefore, to increase the possibility to find the primary failure, the test should be performed with bigger test coverage. Logically, using bigger test coverage requires large number of stressors. Using large number of stressors can increase the possibility to find the primary failure that leads also to higher test effectiveness.

Therefore, to ensure the test effectiveness, the test should fulfill all sub criteria that support the test effectiveness. The sub criteria for the assessment of effectiveness include (1) ability to deal with problems related to technology uncertainty, (2) focus on hard reliability problems, (3) focus on early failure hard reliability problems, and (4) uses large number of stressors to cover failure mechanism (see also table 5.5.1.). A sub criterion (1) is defined because primary failure, early failure hard reliability problems, can be related to extreme products. As stated earlier, extreme products appear due to uncertainty in technology (see section 2.4.4.). In addition, a sub
criterion (4) is defined because to find the primary failure requires an ability of the test to cover failure mechanism that is potentially unknown. Therefore, as stated earlier, by using large number of stressors can increase the possibility to find primary failure.

5.3.3. Position in PDP

The term position in PDP in this thesis indicates the location of a test in PDP. This thesis defines the location of a test in PDP at (1) concept phase, (2) pilot phase, and (3) mass product development phase. The important consideration related to the location of a test in PDP is on time-to-react for a problem. For example, a test that is performed at mass product development phase gives less time to fix a problem if it is compared with test at other phases. In addition, a problem identified lately at the mass product development phase will impact on high cost for problem solving. Ideally, if a test is located at concept phase then it can prevent problems before the product is completely assembled and ready for mass product development. Therefore, the earlier test will give enough time to secure from the cost of bad product quality. Logically, it is better to perform a test earlier in the PDP.

These criteria will be used in section 5.4. to analyze different testing concepts.

5.4. Analysis of Different Testing Concepts

This section presents the analysis from the testing concepts in section 5.2 using the criteria of efficiency, effectiveness, and position in PDP described in the previous section.

5.4.1. Prototype Testing (Alpha, Beta, and Gamma test)

Ozer (1999) classified testing concepts in PDP into test evaluation programs. The test evaluation programs consist of several steps i.e. concept testing, prototype testing, pre-test market, test market, and launch. The alpha, beta, and gamma test are only used in prototype testing. Therefore, as also mentioned in section 5.2.1., they are called prototype testing. These tests are about testing the prototype under several conditions e.g. alpha test is when the test is done in laboratory to see whether the product delivers the intended performance, beta test where people use it for a specified time period, and gamma test when people use it indefinitely and report any problem they may have (Ozer, 1999).

**Efficiency**

The efficiency of prototype testing is assessed using the criteria in section 5.3. Efficiency is assessed by test speed and number of samples required for the test. In the assessment of test evaluation programs by Ozer (1999), he indicated that prototype testing consumes time although it can be reduced using the Internet. He also indicated that a small sample may not represent the population (Ozer, 1999). Therefore it can be argued that prototype testing is considered slow and it requires more samples. On the other word, this assessment indicated that prototype testing is not efficient. Moreover in prototype testing, especially in beta test, the prototype is also tested by exposing it directly to the (representation of) real users. In the real user environment, the prototype faces large number of stressors that
cannot be found in the laboratory conditions. Therefore, the number of stressors that are used in prototype testing is large.

**Effectiveness**

The assessment of effectiveness is based on the criteria of (1) dealing with problems related to technology uncertainty, (2) focusing on (early failure) hard reliability problems, and (3) exposure to large number of stressors. Assessment using these criteria shows that prototype testing is an effective test. The reasons are

(a) Usually the prototype testing aims to find problems related to technology uncertainty (see also section 2.3.2.).

(b) The prototype testing is also aimed to find hard reliability problems, although they are not the early failure hard reliability problems.

(c) Moreover, in prototype testing, the prototype is exposed to a large number of stressors.

**Position in PDP**

As indicated earlier, the location of prototype testing in the PDP is specifically at the prototype phase. Therefore, the prototype testing only serves at the pilot phase or prototype phase in the PDP.

5.4.2. Accelerated Testing

The main consideration of accelerated testing is the ability to perform a test to find hard reliability problems within short test time. For this reason, this test uses several techniques to shorten the test time. Therefore MIL-HDBK-338B reminded that this technique contains basic limitations and every accelerated application is unique. Due to the limitation, it is suggested that before performing an accelerated testing, a preliminary accelerated test is required for a “sanity check” (MIL-HDBK-338B).

**Efficiency**

In terms of efficiency, an accelerated test is considered as an efficient test. It is because this test can be performed in shorter test time with small sample size. However, the limitation in efficiency is that the accelerated test only uses a limited number of stressors during the test.

**Effectiveness**

Although accelerated tests aim to find hard reliability problems, this test is not effective. It is because this test is not specifically aimed to find early failure hard reliability problems. Moreover, due to limitation of stressors used during the test, the possibility to find problems is very limited. Logically, a test can only find problems that are related to the stressors. Therefore, using more stressors will increase the possibility to find failures.

**Position in PDP**

In term of position in PDP, this test is considered very late. It is because accelerated test is applied at the mass product development phase in PDP.
5.4.3. Highly Accelerated Testing

The main consideration in highly accelerated testing is on reduction of test time. Commonly, to accelerate the process, this testing stimulates failures by applying multiple stressors with high level of setting. In application, the process is performed in a testing chamber. The limitation of using a testing chamber is that it can impose a limited stressors set. Therefore, although the technique can provoke failure faster, the ability to find failures depends on the stressors scheme.

Efficiency

This testing concept is an efficient test because it can provoke failure faster using small sample size during the test. However, this concept has a limitation to include a large number of stressors in the test. Consequently, to enable finding failures, this concept depends on the correct stressors scheme. If the applied stressors differ from stressors that cause a failure then the test may not find the failure.

Effectiveness

If assessed using the criteria in section 5.3.2. then this concept is not yet effective. It is because this concept is not always able to find early failure hard reliability problems. This concept is able to find early failure hard reliability problems only when the applied stressors scheme exactly correlate with the failure.

Position in PDP

Similar to accelerated testing, the highly accelerated testing is also very late because it is applied at mass product development phase.

5.5. Comparing Different Testing Concepts

This section combines and discusses the results of the comparison from different testing concepts from the previous sections.

5.5.1. General Assessment

By assessing the existing test concepts, the overview of their strengths and weaknesses can be obtained. The results of assessments conducted by the author are presented in table 5.5.1. This assessment is a subjective view based on experience/ knowledge of the author.

The assessment in table 5.5.1. uses three simple notations. They are ‘+’ indicates “strong”, ‘0’ indicates “neutral”, and ‘−’ indicates “weak”. The idea of presenting table 5.5.1. with these notations is not to get a precise assessment result, but it is to indicate room for improvement. Therefore, logically, the improvement can be made from ‘−’ to ‘0’ then to ‘+’, or from ‘0’ to ‘+’. Consequently, the areas that are denoted as ‘+’ require no improvement because although if improved then the result is considered insignificant with the effort spent for the improvement.
Although Table 5.5.1 shows some weaknesses from the existing test concepts, the major obstacles from the existing concepts are on the effectiveness. Table 5.5.1 also shows that alpha, beta, and gamma tests are considered as the effective tests but not the efficient tests. It is because they can cover broad stressors but they require more samples and longer time for the testing. These tests can cover the broad stressors set because they can involve customers during the test process. In contrast, AL, ST and H AL, ST are the efficient tests but they are not the effective tests. The reason is because they can do testing with limited samples and faster speed but they only cover small dimension of stressors. These tests only cover a small stressors set because they are performed in a test chamber. Commonly, the limitation of using the test chamber is on the inability to include large stressor sets because the chamber capability is very limited. Also testing using a test chamber can only be done in a programmable controlled situation that is in most cases different from the real situation. Meanwhile, in reality, the stressors that cause a failure on a product include a broad range of real life stressors. Consequently, it is difficult to simulate all the real life multi dimension stressors in a controlled test chamber. Further discussion on the limitations of the current concepts appears in the next section.

5.5.2. Discussion of the Limitations of Current Testing Concepts

Although, many test concepts have been developed until now, this thesis only elaborates some of the testing concepts that are used in practice (see section 5.2.). Each testing concept described in section 5.2. has uniqueness and limitations. Their limitations affect the capability of the testing concepts to solve the most recent problems, such as NFF, experienced by industries. Therefore, this section will
specifically elaborate some of the limitations to be improved in the new concept. This section will specifically consider the limitations of the most recent test concept (highly accelerated test concept) because the new concept will be developed based on this concept. The reason is because the efficiency, by means of fast test speed, of the most recent test concepts are acceptable although they are not yet effective. In addition, assessment on highly accelerated test shows that this testing concept is efficient and it is already focused on hard reliability problems. Moreover, in its application this testing method uses a chamber that is also used in the new test method. Therefore, for practicality, it is easier to develop the new testing method based on the accelerated test concept.

The main concern of the highly accelerated test concept is to obtain product weaknesses as fast as possible. Usually, applying a stressor value beyond the product design limit but lower than the destruct limit can accelerate the process. In addition, the stressors are applied in a cycling and repetitive mode, regardless of the amplitude, to increase their severity. The limitations of the accelerated concept are not on the speed but on the test coverage. Usually, this concept lacks the capability to cover a broad range of technical product specifications. Therefore, this concept is good for specific known problems where the stressors are predictable. For the unknown problems, never known before, the concept has difficulties to define the stressors criteria and the limit, the failure criteria and the failure mode. Therefore, for the unknown problems, this concept has difficulty in finding the problems, or if problems are found sometimes they are not the real problems as faced by the customers. Consequently, instead of saving time this concept turns to be time-consuming test sometimes with an ambiguous result.

This thesis argues that these limitations are caused by the limitation of the knowledge regarding unknown hard reliability problems that lead to ambiguous stressors determination including their kinds, combinations, and limits (see table 5.5.1.). Therefore, the accelerated test concept is good for a validation test with known failure mechanism. On the contrary, this test concept has difficulties undertaking an analysis test with unknown failure mechanisms.

Therefore, to overcome the limitation from the highly accelerated test concept especially on the effectiveness, this thesis tries to develop a new test concept called Multiple Environment Stress Analysis (MESA) that will be presented in chapter 6.
CHAPTER 6. MUTIPLE ENVIRONMENT STRESS ANALYSIS (MESA)

The purpose of this chapter is to present the development of a new test concept called multiple environment stress analysis (MESA). The goal of developing this test concept is to compensate the deficiencies, according to the criteria in section 5.3., of the current test concepts in the context of PDPs. The preliminary concept of MESA has been exercised in two cases at a company. Following that, to evaluate the effectiveness and potential efficiency, the concept is evaluated and tested for different applications in six cases at another company.

Unlike in classical testing concepts that are mostly defined for specific reasons, this chapter presents the concept of MESA differently. The concept of MESA is developed in a comprehensive approach so that it can accommodate testing from the beginning of concept development until the analysis of the results.

6.1. Possible Problems in Testing

This section describes possible problems in testing that relate to dynamic systems.

6.1.1. Introduction

The previous chapter has presented several testing concepts that are used in practice. Among them, even the most recent testing concept such as highly accelerated test is considered using the criteria in section 5.3. viewed as an efficient test, but it is not yet effective. Therefore, it is useful to develop a new testing concept as an enhancement of the highly accelerated test concept. Multiple Environment Stress Analysis (MESA) is a new accelerating test concept that utilizes multiple environments as stressors during the test. The acronym of MESA has been defined by the research team, the industrial partner and university. The difference of MESA with other acronyms e.g. Multiple Environment Overstress Test (MEOST) is that MESA includes an analysis phase at the end of the test procedure. Moreover, MESA is also capable of failure analysis. In application, MESA is expected to compensate for the limitations of highly accelerated tests so that it can be both an effective and efficient test concept. The factors that are used to assess efficiency and effectiveness are defined in chapter 5. Among them, table 5.5.1. has identified three important factors that require improvement, especially the factors related to the effectiveness. They are (1) uses large number of stressors with limited experiments, (2) focus on early failure hard reliability problems, and (3) uses large number of stressors to cover as much as
possible failure mechanisms. To accommodate these factors in MESA design, several problems that make the test more complex have been identified. They are (1) problem with escalating time of failure, (2) problem with dimensionality, and (3) problem with dynamic systems. Therefore, in the chosen application MESA will confront these problems.

6.1.2. Problem with Escalating Time of a Failure

This section discusses one of the possible problems in testing, namely the problem of escalating time. The term escalating time indicates the time interval from the starting point of a failure until it is an observable failure. To have a clear understanding of the term escalating time, it is necessary to distinguish the definition of "fault" and "failure". Usually, a failure is initiated by a fault. However, a fault does not always leading to a failure. Therefore a fault, if encountered, may cause a failure (van der Meulen, 1995; MIL-HDBK-338B). Van der Meulen (1995) finds several definitions to describe these two terms. Among them, this thesis refers only to the definition in IEEE STD 610.12-1990. Fault is (1) a defect in a hardware device or component, (2) an incorrect step, process, or data definition in a computer program. In addition, MIL-HDBK-338B defines fault as an immediate cause of failure (e.g., maladjustment, misalignment, defect, etc.). Failure is the inability of a system or component to perform its required functions within specified performance requirements (Van der Meulen, 1995). In addition, MIL-HDBK-338B defines failure as the event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified. If this term of failure is correlated to the common definition of reliability then failure is an opposite of reliability (see section 2.1.1.). Therefore if a system or component contains a fault, then it is still possible to perform its function although the performance may not as good as in normal condition without any fault. However, if the system or component is unable to withstand to the degree of fault then it will fail. The term of escalating time indicates the length of time from fault to failure. The escalating time of a failure differs for every type of failure. A failure can escalate within the range of millisecond up to years. The escalating time within the range in milliseconds can be found in electronics problems, while in minutes can be found in heat problems. Escalating times that take longer than minutes can be found in wear out problems and they can take years to appear. This thesis uses the term of escalating time instead of time-to-failure or failure rate to avoid ambiguity on the meaning. Meanwhile the term of time-to-failure indicates the time required until a system or components fails.

Although this thesis focuses on early failure, class 1 and/or class 2 failures of the four-phase rollercoaster model, the escalating time of early failures still varies from milliseconds up to several months. Therefore, testing on a product should consider the escalating time of the failure. It is because the escalating time influences the design and capability of the testing. Logically, because of practical limitations of testing, shorter escalating time of a failure may cause difficulties. It is because within the range of millisecond the testing must be able to monitor and gather data and/or information of the failure. On the other hand, a long escalating time of failure may lead to long required testing intervals.
6.1.3. Problem with Dimensionality

Usually, a product is composed hierarchically with the lowest hierarchy being components. Therefore, it is not a surprise that the process of finding a failure in a product requires many analyses. The reason is not only that the product consists of large numbers of components but also every failure of a component has different characteristics. Moreover, a component is subject to many failure modes and each of them is triggered by one or more stressors. In addition to the complexity because of product hierarchy, the complexity increases because testing on a larger number of failure modes and stressors requires a correspondingly large dimensionality of the stressor space. Consequently, finding a failure in a product by testing one by one component failure modes is time consuming and costly.

6.1.4. Problem with Dynamic Systems

Although it is easier to assume a failure that occurs in a product as a static phenomenon, this is not a correct assumption. In reality, a failure that occurs in a product is a dynamic complex process. The dynamic complex process is also called dynamic systems because all external factors interact together to influence the failure process. In dynamic systems, it is not easy to determine the causes of the failure because the failure is seldom resulting from a single cause. The factors of a dynamic system include at least (1) the escalating time of failure, (2) the product hierarchy, (3) the mechanism of failure, (4) the type and interactions between product and user, and (5) the testing scheme. As indicated earlier, the goal of MESA is to define the causes of a failure. The classical concept of testing defines them by testing the product until it fails after which the nature of the failure emerges. The drawback of the classical concept of testing lays on the complexity, because to test the product until it fails requires the capability not only to accommodate large stressor sets but also other factors that influence the failure. Therefore, to reduce the complexity can be done at least by (1) using a (small) manageable stressor set, or (2) searching the fault instead of the failure during the test. Although both of them provide advantages, they also have drawbacks. The drawback of using a (small) manageable stressor set is that the tested stressors may not be the (primary) cause of the failure. Further discussion on this topic appears in section 6.1.5. The drawback of searching the fault instead of the failure is that it can be done only if the fault can be identified and observed. For this reason, this thesis defines fault as an indication of the birth of a failure. Therefore, MESA will try to use fault instead of failure as the stopping criteria for a MESA test. Having this enables MESA to reduce test time because the test can be stopped earlier without spending too much time waiting until the failure emerges on (sub) system level.

6.1.5. Handling the Problems

Performing testing in dynamic systems requires a lot of time especially if the testing is performed using the classical one-at-a-time technique. Therefore, it needs help from other techniques. This chapter incorporates a Design of Experiments (DoE) technique in the application of MESA. The reasons of incorporating DoE are that it has advantages to help solve the problem of (1) dimensionality, and (2) test time. However, besides the advantages, DoE has also drawbacks especially when handling
problems in the dynamic systems. One of the drawbacks is that DoE is commonly used for static problems (see section 6.2.2. and 6.2.3.). Therefore, provisions must be made if attempting to incorporate DoE in dynamic systems (see section 6.2.4.). Section 6.2.2. further discusses an alternative DoE technique that can be used such as by sequential DoE (Fedorov, 1972). The discussion on the topic of DoE can be found in the next section.

6.2. Design of Experiments (DoE)

This section presents an overview of DoE in the context of testing.

6.2.1. What is DoE?

Although DoE is a popular term, the meaning is not familiar. Therefore, it is not a surprise if the term of DoE is sometimes associated as a complex statistical method of doing experiments. This thesis will only focus on the use of DoE instead of on the process of doing it. The reason is that this research will only use DoE as needed to help improve the efficiency and effectiveness of MESA.

According to Condra (1993), Design of Experiments is a method of systematically obtaining and organizing knowledge so that it can be used to improve operations in the most efficient manner possible. Condra (1993) also shows that DoE can only help and organize the knowledge already there. This indicates that DoE can be used for MESA if the knowledge of MESA has been built. Therefore, although DoE is useful for MESA, the important point for this thesis is on how to develop the knowledge for MESA. Later if the knowledge has already been built then DoE will be used to improve it.

6.2.2. DoE in the Context of Testing

DoE is used to help organize the process of searching dominant factors and interactions between those factors in an efficient way (Condra, 1993). In this respect, DoE is claimed as a powerful and an efficient tool. However, in common application, DoE is used to handle problems categorized as static systems. In static systems, a problem is caused by static factors such as, in the testing context, stressors. The indication of static factors includes at least (1) enough time for observation, (2) observable response, whether in qualitative or quantitative measure, (3) exact setting limit of the level such as low, medium, or high limit, and (4) limited time for testing. Therefore, in static systems, although there is large number of factors, DoE can reduce them significantly.

In the context of MESA testing, DoE will be confronted to problems that are dynamic (see also section 6.2.3.). In this context, DoE may be applied differently than in the classical way of performing it. One method that can be applied to handle problems of dynamic systems is possibly by sequential methods of DoE that was discussed by Fedorov (1972). For such a complicated experiment and long investigation e.g. in dynamic systems the sequential methods of DoE may be appropriate. The concept of sequential DoE is to reduce the complexity by dividing the experiments into several steps. At each step a design is carried out and followed by analysis of the experiments.
after each step (Fedorov, 1972). Although this is not a new method, it can be used as an alternative for handling dynamic problems.

6.2.3. DoE: Combination of Static Factor Settings

Although this thesis is not specifically intended to discuss the mechanics of DoE, it is necessary to have basic understanding of DoE. Usually, as indicated in section 6.2.2., the objective of using DoE is to help define dominant factors and to know interactions between those factors. The objective can be achieved by any DoE technique, although each of them has different characteristics. In general, regardless the DoE techniques applied during the experiment, DoE will test a subset of or all combinations of factors to define the dominant factors and their interaction. Mostly all factors are static so that the complexity of the experiments is manageable. In a static DoE experiment, every run is performed within a limited time so that it is not a limitless experiment. On the contrary, in a dynamic system the experiment in a run can be time consuming. Therefore, regardless the combination of factors in a run of a static experiment, the experiment can be performed within a certain time limit. So that, it is clear when to start and when to stop the experiment. Commonly, the experiment in a run will be stopped if all combinations in the corresponding run have been completed.

6.2.4. Applying DoE on Dynamic Systems

This thesis does not intend to use DoE in a dynamic system directly like in a common DoE application. Generally, regardless of static or dynamic systems, this thesis intends to use DoE to help reduce the MESA test time. To be able to reduce MESA test time, DoE is expected to:

(1) reduce inexact determination in MESA test plan. In this task DoE is expected to,
   (a) help screen out large number of stressors list used during MESA test into a manageable stressor set.
   (b) help on setting up an accurate MESA test scheme.

(2) enable an inexperienced team to perform the test in a traceable process with fewer mistakes. This implies that an inexperienced team can perform a test with similar result as an experienced team.

Consequently, if the inexact determination in the MESA test plan has been reduced using DoE then it enables an inexperienced team to perform MESA test in a traceable process with less mistakes. Therefore, referring to the factors in dynamic system mentioned in section 6.1.4., DoE can help to efficiently handle the factors number (4) the type and combination of stressors, and (5) the testing scheme.

The other factors in dynamic systems as indicated in section 6.1.4., other than factors number (4) and (5), are (1) the escalating time of failure, (2) the product hierarchy, and (3) the mechanism of failure. At this moment, they are considered as difficult factors to be handled in the MESA test. The reason is that these factors cause the execution time of MESA becoming longer or in worst case it never comes to an end especially if a failure cannot be found. For example, if the stopping criteria are based on finding a failure then as long as no failure is found the experiment will not stop.
Therefore, testing in dynamic systems is complex and tricky. The next section will elaborate further on these factors.

6.2.5. Testing on the Difficult Factors of Dynamic Systems

Section 6.2.4. indicates three factors of dynamic systems that are difficult to handle. They are (1) the escalating time of failure, (2) the product hierarchy, and (3) the mechanism of failure. The escalating time of failure indicates how fast a failure can escalate from the first time it initiates to an observable failure. Usually, it is not known yet the escalating time of a failure that will be tested using MESA. If the escalating time of failure is very short, such as milliseconds, the information is impossible to be captured during the test. In addition, usually for a new failure that is never known before, it is not known yet the possible location of the failure in a product hierarchy. In this situation, usually the entire product will be tested or if it is tested at the suspected hierarchy then the location is defined base on experience. Furthermore, for a new failure that is unknown before, the mechanism of failure is likely also unknown. As a result, the determination of stressors type and level will be based on experience. These difficulties lead to inexact determination because commonly they can only be defined by experience. This situation indicates that MESA requires other non classical DoE techniques to help overcome the difficulties.

Before discussing the roles of DoE in MESA, the next section presents the details of the MESA design.

6.3. MESA Design

The goal of this section is to present the process of designing MESA. The process is initiated by establishing requirements for MESA. After that, theories that support the design of MESA are presented. Including in the discussion are the concept of MESA, MESA development, and the possible roles of DoE in MESA.

6.3.1. MESA Requirements

The previous chapter, chapter 5, summarizes the criteria for testing and the limitations of current methods. Moreover, the discussion regarding the limitations of the current methods indicates that gaps exist.

Before presenting the details of MESA, this section will summarize the requirements for MESA. The requirements for MESA can be categorized as follows:

1. Alignment with goal to tackle the NFF
   - Specific (MESA must address specific hard reliability problems)
   - Competent (MESA must be able to find failures with limited failure knowledge)
   - Effective (MESA must be able to find primary failure, hard reliability problems, during the test)
   - State-of-the-art (MESA must be able to include the non-traditional stressors)
   - Broad (MESA must have broader product specification coverage)
2. Alignment with capability of analyzing problems
   - Complete (MESA must have complete purpose i.e. Analysis and Validation)
   - Systematic (MESA must have the method of engineering analysis test)

3. Alignment with business pressures
   - Efficient (MESA must be fast and can be performed with limited number of products)
   - Proactive (MESA can be used in very early PDP)
   - Flexible (MESA must fit with existing PDP and be able to interact with other tests in PDP)

From these requirements and as indicated in table 5.5.1., MESA will specifically improve on the weaknesses and maintain the strengths from the most recent test methods. The noticeable weakness is on the effectiveness and the strength is on the efficiency. Moreover, as indicated in table 5.5.1., to improve the effectiveness the focus of the test must be given to find early failure hard reliability problems. In addition, to enable finding the failure, the test must use a large number of stressors. Additionally, it is expected that the test can be performed at early phases of PDP.

The theories that support the design of MESA are discussed in the following section.

6.3.2. The Mechanism of Failure

This section discusses the mechanism of failure of a product or a component. The understanding of the mechanism of failure creation is important for MESA especially for those in phases 1 and/or 2 of the four-phase rollercoaster model (see section 2.4.1.). If the mechanism of the failure has been understood, then the concept of MESA can be developed to overcome it. This thesis adopts the stressor susceptibility concept (see section 2.5.), and principle of multiple stressors to explain the failure.

6.3.2.1. Principle of Multiple Stressors

Basically, a single stressor or multiple (combinations of) stressors can cause a failure. If a single stressor creates a failure in a product or its component, then the level of the stressor is usually above the technical specification. On the contrary, if multiple (combinations of) stressors create a failure in a product or its component, then the levels are not always above the individual technical specifications (Brombacher, 2000). A multiple (combination of) stressor can create a failure in a product or its component although all stressors levels are below the corresponding technical specifications. Logically, this happens because the strength of a product or its component cannot withstand to the severe level of stress. Although the mechanism of failure that is caused by multiple stressors combination is not yet clear, it is possible that the multiple stressors combination can create a failure faster than only with one stressor. This concept relates also to stressor susceptibility concept in section 2.5. that explains failure mechanism on a product or components. Therefore, this thesis will explore the method of testing that utilizes the concept of multiple stressors combination. Logically, to create an efficient test, the new testing method must define the right stressors combination. It is because the speed of the test to provoke failure can be achieved by performing the test with the right combination of multiple stressors.
6.3.2.2. Method of Creating Failures

There are two possibilities to create a failure in a product or its component. It can be done by changing factors of stressor, factors of susceptibility, or both. A failure appears if stressors probability density function and susceptibility probability density function are overlapping (see also section 2.5.). Therefore, if the overlap is increased then it can provoke a failure faster. Furthermore, at each factor, the probability and the level are the aspects that can be modified. To create the overlap can be done by:

- Changing the factors of stressor and keep the factors of susceptibility fixed. There are two ways to create failures by changing the factors of stressor.
  
  1. Increase the probability level of (extreme) stressor.
      The idea of this approach is to increase the overlap between the stressor probability density function and the susceptibility probability density function. One way to do so is to increase the probability level of stressor (Figure 6.3.2.2. illustration a) such as by increasing the frequency or operation cycles.

- Changing the factors of susceptibility and keep the factors of stressor fixed. This strategy, theoretically, can increase overlap between the stressor probability density function and the susceptibility probability density function. Although this strategy is, theoretically, possible by the usage of weak products, this research will not use this strategy (Figure 6.3.2.2. illustration c).

Figure 6.3.2.2. Method of Creating Failure
(adopted from Lu, 2000)

  2. Increase the level of (extreme) stressor
      A different approach can also be applied using the same idea. The overlap between the stressor probability density function and the susceptibility probability density function will increase if the level of extreme stress is increased (Figure 6.3.2.2. illustration b).

- Changing the factors of susceptibility and keep the factors of stressor fixed. Moreover, weak products also can be obtained from the manufacturing. Commonly in product development process control chart, because of high material and/or process variation, the weak products reside beyond the control limit. These products are weaker if they are compared to the products that reside within the control limit. However, the weakening process is not due to ageing i.e. not time dependent.
6.3.3. Concept of MESA

The concept of MESA is formulated according to the requirements set in the previous section. MESA is a (accelerated) test with the purpose to surface the (design) flaws on either innovative or repetitive products to be an observable failure. The concept used in MESA is to apply a relevant combination of (extreme) stressors on a determined test scheme early in the PDP process then followed by a root cause analysis. Unlike the common test methods, the stressors used in MESA are both traditional and non-traditional stressors. To provoke failure, MESA stresses the object under multiple worst-case environmental and usage conditions to bring to the surface the weaknesses or flaws of the design in an efficient way; at minimum sample size, and within the shortest time. Basically, according to section 6.3.2.2., this approach provokes failure by increasing the level of stressor. Furthermore, to increase the probability of stressor is done by applying the stressor in cyclic mode with a certain frequency. The applied cyclic configuration depends on (1) the type of failure being searched, (2) the capability of testing equipment, and (3) properties of the product. The level of stress and the cycling mode applied on the product, make this test different from other available tests.

The concept of MESA has been developed jointly with a multinational corporation that produces high volume consumer electronics. For this reason the company has invested in a test chamber, which can generate and simulate the basic stressors i.e. vibration and temperature.

6.3.4. MESA Development

In the development of MESA, it is important to understand the objective. It is also important to share the information needed to the parties involved. The reason is that during the development of MESA, not only people from the development department but also from other backgrounds should be involved. Therefore, to conduct the MESA test, a guideline that covers the detail activities must be established.

6.3.4.1. The Objective of the Development of MESA

The objective of the development of MESA is to develop an accelerated engineering testing concept to tackle the early reliability problems, class 1 and/or class 2 failures of the four-phase rollercoaster model, at early phases of PDP. The testing concept, namely MESA, should be more effective with at least similar efficiency than the most recent testing concepts. To assess the workability of the MESA testing concept, it is then tested in real industrial application. Furthermore, to improve the efficiency and effectiveness, it is proposed to accommodate DoE into MESA.

6.3.4.2. MESA Test Protocol

In order to perform the test effectively, this research uses three phases that have to be performed during the test and it is known as a test protocol. They are (1) pre-test, (2) test, and (3) post-test phase. Moreover, to achieve the optimum result, activities on these phases require adjustment and adaptation to the real situation. For example, a test that has similar characteristics than a previous test will require less preparation than a test that is performed for the first time. The complete steps in the MESA test protocol are shown in figure 6.3.4.2.
1. Pre-test
The pre-test is aimed at saving time on later activities by investing time in preparation activities. Logically, this phase ensures that the test will be carried in a well-prepared condition. This phase consists of theoretical and practical pre-test activities. In theoretical pre-test activities, at minimum the following sub-activities must be performed:

Theoretical pre-test activities:
- Define the test success criteria
- Define the product failure criteria
- Define the type of a product or a component to be tested
- Determine the stressors
- Determine operating limit, sample size, and special equipment/tools.
- Determine the type of analysis and the experiment setup
- Develop a test plan

While the practical pre-test activities consist of:
- Preparing test equipment
- Establish (destruct) limit
- Determine MPOS (Maximum Practical Overstress Test Limit)
- And other activities related to practicality of the test

As mentioned earlier, an apparent failure is not always a primary failure or the failure that is searched (see section 5.3.2.). For that reason, to avoid ambiguity between the primary failures with the false failure during the test, parameters that will be used to differentiate them have to be clearly defined on beforehand. In addition, this phase should define failure detection criteria for immeasurable failures because not all failures can be detected by measuring them directly. Therefore, especially for immeasurable failures, the failure detection criteria may rely only on visual observation and examination.
2. Test
Activities in this phase are mostly on executing the test, recording the data, and observing the failure. In most cases, due to the complexity of the test, an automatic method is required to efficiently execute the test. An automatic system is also needed for the failure detection that is used during the test. For example, if the automatic system is unable to detect failure by measuring the response then a special method to detect failure such as by visual observation has to be used.

3. Post-test
Activities in this phase are listing the events of failure and conducting assessment of the failure. These activities are important for further root cause analysis of the failure. Basically, this phase is the analysis step in MESA. Moreover, attention must be given before using the results to draw conclusions. It is important to note that the results should be validated before making any conclusion.

The next section specifically discusses the possible roles of DoE in MESA.

6.3.5. The Possible Roles of DoE in MESA

The possible roles that DoE can perform in MESA are discussed in this section.

6.3.5.1. Using DoE to accelerate the testing process
As indicated in section 6.1.3, analyzing a failure using classical testing methods can consume a massive test time. Therefore, using these methods is not feasible because it results in high cost of testing. Consequently, to reduce the cost, the testing must be carried out in the shortest possible test time. This indicates that the testing process must be accelerated. Among other methods to accelerate the process, the most recent test methods have adopted the techniques of acceleration as described in section 6.3.2.2. Usually, (1) by applying the high level of stressors, and/or (2) by increasing the probability level of these stressors can accelerate the test. Although the most recent test methods work well, they are unable to precisely define the exact level of the stressors and the test scheme. Mostly, the stressors level and the test scheme are defined by the brainstorming technique. Commonly, brainstorming relies on experience and knowledge of the team. Consequently although the recent test methods can accelerate the testing process, it contains high risk of unsuccessful test especially when it is performed by a new team that has never been exposed to similar problems before. Therefore, this method is very knowledge and experience dependent. For these reasons, DoE is needed to help MESA define the stressors level and the scheme to become more objective and precise. It is expected that DoE can reduce the dependency of knowledge and experience from the team as well as avoiding guessing. Furthermore, DoE enables MESA to be autonomous so that any team can perform it in less time.

6.3.5.2. Using DoE to handle large stressor sets
This thesis considers two test strategies to handle large stressor sets (1) reduce the number of stressors until they are manageable, and (2) keep large number of stressor set during the test.

The advantages of using the first strategy are (a) the applied stressors are manageable, and (b) the test preparation is easier. However, the major disadvantage of the first
strategy is that the test risks of finding no failure because limited stressors may not cover the entire range of potential failure mechanisms. This is also considered as one of the drawbacks in effectiveness from existing test methods (see section 5.5.1.). However, this approach is used during the first case study because when this case study is performed the goal is not on improving the effectiveness yet but on finding a failure. Therefore, to reduce the test time and the complexity, MESA must reduce large numbers of stressors into small manageable stressor sets. This can be done by using either the brainstorming technique, other problem prioritization technique, or a common DoE technique. Logically, it is difficult to reduce the large number of stressors directly into a small number. High reduction of stressors will also affect the effectiveness of testing because testing with a very small number of stressors may not be effective for MESA. Therefore, this research will consider the reduction of stressors not as the primary goal but more importantly this thesis considers the manageability of multiple stressors as the primary concern. As long as the number of stressors is manageable and the test consumes not much time and cost for the user, then the test can proceed. Commonly, DoE techniques can help to reduce effectively the large number of stressors such as by screening DoE. The important consideration when using a DoE method is on its practicability and complexity. In practice, people are not aware too much of the details of DoE but they are more aware on the result of DoE. Therefore, this thesis will not stick to one method but encourage applying a manageable DoE method.

The second strategy is considered more difficult because it requires an ability to handle a large stressor set during the test. Therefore, it requires an efficient DoE technique in order to handle large stressor set during the test. The disadvantage of the second strategy is on the complexity of the test. However, the second strategy provides greater advantages in finding a failure especially the early failure hard reliability problems. It is because by using a large stressor set during the test enables the test to cover more failure mechanisms. Therefore, the second approach enables MESA to find a failure with higher possibility and to outperform the recent test methods in term of effectiveness.

6.3.5.3. Using DoE to determine the stressors scheme and limits

As indicated earlier, the most recent test methods such as Highly Accelerated Test concepts, those that use the concept of multiple stressors, have weaknesses on defining precisely the level of stressors. Commonly, the guideline of defining the (maximum) level setting of the stressors is based on intuitive or practical rules of thumb. Although, the step-stress method is available that can help on defining the maximum stressors level by testing the product until it fails (MIL-HDBK-338B). In reality, it takes a complex process to define maximum stress level. The maximum stressor level of a product to fail is called destruct limit. Usually at this level, destruct limit, the product fails. Commonly, the determination of the destruct limit can be predicted with empirical equations (Bothe & Bothe, 2000). Similarly, the ability to define the exact scheme of the test is also unclear. This thesis expects that DoE can also help on defining the correct setting for the stressors and the scheme. Logically, it is not a big problem in practice. However, this becomes uneasy and complex because MESA uses multiple stressors in dynamic systems while DoE is applied mainly on static systems. For this reason, this research suggests to use DoE to define the stressors limit and their scheme in MESA test. It is expected that by applying DoE on the determination of stressors setting and their scheme can help (1) accelerate the test
time, (2) ensure the successful result of provoking failure, and (3) ensure engineering root cause failure analysis to be performed with exact stressors.

### 6.3.5.4. The scenario of involving DoE in MESA

The scenario that involves DoE techniques to handle the problem in MESA is presented in Figure 6.3.5.4. One of the important considerations on designing DoE is that the factors involved in the problems can be qualitative and quantitative. Therefore, to be able to measure the response, the qualitative factors must be converted into measurable factors.

![Figure 6.3.5.4. Scenario to Include DoE in MESA Test](image)

Figure 6.3.5.4. shows that there are two possibilities for accommodating DoE into MESA i.e. (1) Screening DoE, and (2) Analysis DoE.

1. **Screening DoE**
   - DoE can be applied to screen the large number of stressors into a small manageable stressors set. In screening DoE, MESA is not necessary to perform a continuous cycling test but to perform a step-by-step test experiment. For this reason, the stressors will be set such as into two settings; the worst case and the best case. To steer the MESA test, the programmable control system must be adapted to a step-by-step test mode. This test aims not to provoke failure on the module but to define dominant stressors. Therefore, it is not necessary to do a test until the module fails. This test requires only completing all runs that have been defined in experiment design and to record responses from all runs. The results will be used to define the dominant stressors that bring impact to the important failure parameter. Moreover, if the test is aimed to define the failure then the same process can be repeated until the module fails. After that, the dominant stressors can be used in MESA test to make the test simple and fast.

2. **Analysis DoE**
   - Figure 6.3.5.4. shows that DoE can also be used to define correlation of the parameters. For this case, it uses an analysis DoE. Analysis DoE is aimed to define relation of the stressors to the failure. So that the failure can be predicted for the purpose of improvement. The analysis DoE can be performed after the first MESA test has confirmed that the dominant stressors are able provoke the failure. Commonly, an analysis DoE is also a static system.
The next section discusses topics that are necessary in the implementation of MESA.

6.4. MESA Implementation

In MESA implementation, it is better to assume that there is potential uncertainty especially for newly developed products where the available knowledge is limited. Therefore, to minimize the potential uncertainty, it is necessary to have a strategy for implementation and a solid test-plan as discussed in the following section. This section also emphasizes the importance of the validation techniques during MESA implementation to minimize unreliable results.

6.4.1. Strategy for Implementation

Generally, in MESA implementation, the result of the test can be categorized into two possibilities i.e. success or not-success. Success means that the objective of the test can be achieved at first trial within the predicted time frame. Not-success means that the objective of the test cannot be achieved at first trial. There is no fail result in MESA even for the test that is categorized as not-success because in the test process there is always something that can be learnt. Therefore, the strategy of MESA implementation is aimed at ensuring success at the first trial of the test. Other reason of ensuring success at the first trial during the test is on test cost. It is because if the test is not successful at the first trial then the test must be repeated until it is successful. In this situation, the test costs consist of both cost for the initial test and cost for the test repetition. Moreover, the strategy for MESA implementation is also to prevent the cost that emerges because of longer test time. It is because if MESA requires longer time to get success then it will also impact the test cost. For these reasons, during the implementation of the MESA case study, this research uses the strategy of migration more activities into the pre-test phase. The reasons are (1) to ensure that all scenarios for the test have been clearly defined, (2) to ensure that the tester is familiar with the test procedure, (3) to ensure that all worst-case scenarios have been considered, (4) to save time by performing the possible activities earlier, and (5) to minimize risks during testing. The other strategy applied during MESA implementation is to stick rigidly to the test protocol. The reason is that to ensure the success of MESA test, the process during the test must not be disrupted for any reasons. For example, the disruption during MESA can occur because of making a conditional adjustment that is affected by improper setup and/or improper pre-test activities. Therefore, it is urged to stick rigidly to the test protocol so that unnecessary disruption during MESA can be avoided.

6.4.2. Test Plan

When performing MESA, a test plan is needed to ensure the success of its implementation. The other reason of defining a test plan is to prevent a faulty test. In application, it is possible that MESA will find no failure at all. Therefore, to avoid the faulty test, a test plan is required and it must be consistently followed.

A test plan can be in a form of a guideline that covers the activities prior, during, and after the test. It includes technical detail activities such as how to perform a team brainstorming when selecting stressors, and their limits, how to setup criteria of failure, how to identify failure, how to measure the failure, etc. The technical details
on the test plan can be derived from the theoretical background and/or from practical experience. It is important to note that a test plan only helps to guide the management of the testing process from the start to the end of the process. An example of the structure of a test plan is shown in the figure 6.4.2.

![Test Plan Structure Diagram]

Figure 6.4.2. An Example of a MESA Test Plan Structure

6.4.2.1. Handling large stressor sets

It is possible that defining stressors for MESA test, for example by means of a brainstorming technique, can result in a big quantity of stressors. If MESA has to accommodate them then there are two possible scenarios (1) reduce the number of stressors, or (2) keep the existing large number of stressors. In the first scenario, the advantage of reducing the number of stressors is to ensure that MESA test will become simple and uncomplicated. However, it also risks of having faulty results. In the second scenario, the disadvantages of keeping a large number of stressors are (1) complicate the MESA test, and (2) require a lot of time to perform the test. However, the advantage of accommodating large quantity of stressors, they enable MESA to find the searched failure with high possibility of success. In addition, using a large quantity of stressors can increase the test effectiveness at the cost of losing efficiency (see also section 5.3.2.). However, if accommodating a large number of stressors in the test then an additional technique is required in order to make the test fast, simple, and uncomplicated. For this reason, as mentioned earlier, MESA can accommodate a Design of Experiment (DoE) technique in its application. Therefore, a DoE technique must be explicitly defined in the test plan. This technique mainly helps to define the interaction between stressors and to define the significant stressors within short time. If the significant stressors that contribute to failure have been defined, then further test detail such as the determination of the stressors level can be performed. Furthermore,
to handle the complex experiment with large numbers of stressors, a programmable automatic test technique is required.

**6.4.2.2. Determination of stressors limit**

Other important factor in the test plan is on the method of defining the stressor limits. As mentioned earlier, MESA will use stresses higher than the specification limit or design limit but not more than the destruct limit or only up to maximum practical overstress limit (MPOSL). Logically, to define the MPOSL the design limit and the destruct limit must be known. Bhote & Bhote (2000) defined the design limit as the highest of the engineering specification limit and the highest field stresses. It is possible that the design limit can be higher than the destruct limit. If it is the case then the MPOSL is impossible to be determined. For simplification, this thesis will use the engineering specification limit as design limit. The destruct limit is the highest limit of stress if a product is exposed to a stressor until it fails. It is a tricky situation because the destruct limit for a product will be different if it is exposed to one stressor and to multiple stressors. For simplification this thesis will use a destruct limit that is determined by one stressor. There are some methods that can be used to define the destruct limit such as by (a) step stress, or (b) progressive stress (MIL-HDBK-338B). Step stress is a method of defining the destruct limit using one stressor. In the process, initially the specimen is exposed to a certain stress limit for a period of time then it is exposed to a higher level of stress for a certain time. The process continues at increasing stress until the specimen is failed. Generally, in step stress the stress is increased step by step. In contrast with progressive stress, the stress is increased continuously until the specimen is failed. Therefore, there is no time to observe the behavior of the specimen at each step of the process. In MESA, the step-stress method is used to determine the destruct limit. The reason is that using step stress enables to record or to observe the failure process and the failure behavior. It is important because later the knowledge of failure behavior will be used as a reference in the root cause analysis. Moreover, the goal of the stressor limit determination is not on the speed. Therefore, it is not necessary to define the stressor limit in the fastest way.

Bothe & Bothe (2000) defined a practical formula to define the level of MPOSL. According to Bothe & Bothe (2000), MPOSL is lower than the destruct limit by one third of the distance between the design limit and the destruct limit. However, this thesis will not specifically adopt this definition of MPOSL. What is important for MESA is that the maximum overstress limit must be lower than the destruct limit. It is because MESA will use this number as a setting point for the stressors in the test scheme. The advantage of having a high limit of MPOSL is that it could accelerate the process of testing. The disadvantage is that if the setting is too high then it can influence on the cycling process. This means the stress can be set high enough as long as it is lower than the destruct limit. Another important consideration in setting the maximum overstress limit is that the limit must be set at a level that allows all stressors to perform at minimum one full cycle before the specimen fails. The reason is that if the maximum overstress setting is too high then the specimen will fail only by some stressors without allowing other stressors to complete their cycle. It is also important to note that to define the dominant stressors that create failure requires a completion of cycling by all stressors during MESA test. It is because failure may be created by interaction of multiple stressors (see section 6.3.2.1. and 6.3.2.2.). Moreover, finding appropriate stressor limits that allow at least one full cycle from all
applied stressors is not easy. In application this practice contains several difficulties. Therefore, it is necessary to validate the test result before it can be accepted.

**6.4.2.3. Determination of sample size**

A second important consideration in the test plan is the determination of the number of the specimen or sample size. This thesis will define the number of specimen based on the logical justification. Logically, more samples are better than fewer samples if they can be afforded with acceptable cost. It is because with more samples will increase confidence level during the analysis of test result. Usually, samples are correlated with the cost especially for newly develop products. In newly developed products there are limited samples available that can be used for testing. Therefore, MESA must be able to perform the test with minimum sample size. Roughly, samples required for MESA can be allocated for the following:

1. Samples for defining stress level
2. Samples for MESA test
3. Samples for validation
4. Samples for backup

There is no exact figure on the sample size. Practical rules of thumb during the case study define the samples size roughly around 20 to 40 pieces.

**6.4.3. Test Validation**

Test validation is important to ensure that the test has been correctly performed and the result is validated. The result of validation will be used for further analysis to reach the conclusion. In principle, the validation is about the replicability i.e. repeatability of the test and reproducibility of the failure. Repeatability is the ability to achieve the same result when repeating the test using the same scheme and equipment at the same place and location. Therefore, the test must deliver the same result with the same test scheme, if not the test is considered invalid. Reproducibility is the ability to reproduce the same result with the same test scheme after some time using different equipment at different place and location. Therefore, if the result is different after being repeated with the same test scheme then the result is irreproducible and it is considered invalid.

Logically, this validation method requires at least two repetitions of the same test that must deliver the same result. If this requirement is fulfilled, then the test and the result are considered valid regardless of the test sequence applied during the validation test.

**6.5. Discussion**

This section discusses topics that are considered important for the success of MESA.

1. The role of DoE in MESA

   DoE is required to reduce a large number of stressors into a small, manageable set of stressors and to effectively define the dominant stressors from them (recall sections 6.3.5.2., 6.3.5.3., and 6.4.2.1.). Generally, the roles of DoE in MESA can be summarized as follows:
• Although MESA can handle all the combinations of stressors, this method is considered time consuming, not efficient, and costly. Therefore, DoE is needed in order to make the test efficient.

• In pre-test stressors selection, the dominant stressors that create failure may be defined by using a common technique such as fish-bone diagram. Moreover, to have a qualified result and analysis, a team is expected to have both a diverse background of knowledge and lifelong experience in a specialized field. It is because if a team with less knowledge and experience performs the pre-test stressors selection then the probability to make faulty results and/or wrong analysis is high. Therefore, DoE is needed in the pretest stressors selection to ensure that a team with less knowledge and experience can perform it with qualified result. For example, the team can perform a screening DoE to search dominant stressors that give response as a sign of failure. As a result, only the dominant stressors that have response to sign of failure will be used during MESA test.

• The replicability of a failure sometimes is needed. For example, on a situation where the effort of improvement from a failed product gives no indication of success. In order to trace back the causes of failure, a failure replication is needed. This process will not be easy if the method of stressors determination and failure analysis has been done on a qualitative base. Therefore, DoE is needed to ensure that they are defined on an exact base. Therefore, it enables the traceability process.

• The cost of MESA is high; therefore to reduce the cost, MESA has to be performed at the shortest possible test time with high quality of result. For this reason, DoE can be used to help reducing the cost by performing an efficient and effective test and ensuring high quality of result.

2. Knowledge acquisition
MESA also considers knowledge acquisition as one of the important factors for success. The reason is because the repetition of thorough analysis on similar problems with MESA is seldom to appear. It is because performing the same problems more than once using MESA will be costly and unnecessary. Logically, the same problems can be analyzed by other techniques using the knowledge acquired during the first problem analysis with MESA. This is known as “economy of experience”. However, this can only be possible if knowledge acquisition during MESA tests is properly managed. Therefore, ensuring knowledge acquisition is a concern of MESA such as by having an explicit test plan, good data recording system, structured planning, execution, analysis, and reporting.

3. Share of information from other tests
MESA as other test methods also contains drawbacks. Therefore, it is necessary for MESA to interact with other test methods in order to compensate the drawbacks. However, not all information from one testing method can be shared to other testing methods because each of them is designed with different purposes. The basic idea is to promote the share of information between MESA and other test methods to the optimum level especially to information that is useful for others. Therefore, to achieve the optimum share of information, the role of each testing
method that relates to hard reliability problems and the position in the PDP must be clear.

Case studies on several industrial problems have been done with the purpose of demonstrating the workability of MESA and improving its effectiveness in handling the problems. The results of the case studies can be used not only to show the strength and weaknesses of MESA but also to answer the research questions 2 and 3 of this research. The complete case study of MESA appears in chapter 7.
CHAPTER 7. MESA CASE STUDY: RESULTS AND EVALUATION

The purpose of this chapter is to present the use of MESA in actual industrial environment using case studies. The discussion in this chapter will be based on one case study. Further discussion from the other cases appears in appendix E. The cases have been carried out at an industrial partner in a normal industrial context. During the case study, MESA has been applied in various industrial problems. To present the case study, this chapter is organized as follows: initially the strategy for MESA implementation is discussed. It is followed by a discussion of the case selection criteria. After that the demonstration of a step-by-step case example is presented. Following that the case summary is presented and it is followed by the evaluation of the case study. Finally, this chapter presents the general evaluation of MESA.

7.1. Introduction

In order to validate the concept of MESA in chapter 6, MESA is tested in a real industrial application. The idea of applying MESA in real industrial application is not only to demonstrate the ability of MESA but also to observe the weaknesses of MESA for further improvement of its effectiveness and efficiency. Especially for this research, the results of the case study will be used to answer the research questions 2 and 3. Therefore, to draw a valid conclusion, the case study is designed to cover various types of industrial problems. The analysis will not be presented in this chapter but it will appear in chapter 8. The next section presents the case study.

7.2. Case Selection Criteria

During the preliminary case study, several limitations that can impact the success of MESA have been identified. They are the difficulty to define the problems to be tested, the number of samples to be used, the limitations of the test bench, the limitation of knowledge and experience of previous tests, the number of people involved in the test, the high costs involved in setting up the chamber, etc. With these limitations, the percentage of not-success during the first trial is considered higher than the percentage of success. Therefore, to increase the success possibility, the case study of MESA is divided into two steps i.e. (1) the first step focuses on setting up the structure of MESA, and (2) the second step focuses on improving the effectiveness. In

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2 The case study was performed together with an industrial partner with the outcome of 2 master theses and papers. Thanks to students Hermans (2002), Jager (2004), and from the industrial partners Willibald Bacher, Nigel Radford and Christian Schmidt for their outstanding contributions.
the first step, the activities are divided into two parts (a) physical activities that concentrate on the setup, and on improving the chamber, and (b) non-physical activities that concentrate on the development of a MESA test protocol. Moreover, the activities in the second step are to focus on achieving the objective of MESA. As indicated in section 6.3.4.1. the objective of MESA is to develop an (effective and efficient) accelerated engineering test concept to tackle the early reliability problems at early phases of the PDP. In the first step, the physical activities are handled by industrial partner and the non-physical activities are handled by university. Basically, the first step requires more time and resources than the second step. The reason is that these activities are new so that the team requires to setup from the beginning. The general overview of the fist step can be seen in Hermans (2002).

This chapter specifically discusses the second step because most parts of the activities in the first step have been covered in the previous chapters. One of the important factors to enable efficient testing is on defining the requirements for problems to be tested by MESA. The requirements are necessary because in practice there are several types of industrial problems that need attention for a credible root cause analysis. However, MESA cannot handle all the problems simultaneously because (a) it can be a costly test, (b) it is possible that some problems require no MESA to handle them. Therefore, the available problems must be screened out and reduced to only the most potential problems for MESA. To define the requirements, it is important to consider at least (a) reasons for testing, (b) type of problem, and (c) knowledge of the problem.

The next section demonstrates a step-by-step process in MESA implementation.

7.3. Demonstration of a Case

During the implementation of MESA, several case studies have been performed. However, this chapter demonstrates the implementation of MESA referring to one of the cases. Moreover, other case studies on MESA that have been performed during this research can be found in appendix E of this thesis. During the case study, although the test could be managed using an automatic control system, the test was predicted to be very time consuming. Therefore, to reduce test time, it was proposed to apply DoE after the first trial. According to the MESA test protocol in figure 6.3.4.2., DoE could be performed after the result has been verified. However, on the first trial of MESA, the team did not adopt DoE yet for the following reasons (1) the team had no sufficient knowledge to perform DoE on MESA because it was new for the team, and (2) the team was unsure of its capability because the team considered DoE practically difficult. These were the roadblocks in adoption of DoE. Therefore, in the first MESA test, DoE was only introduced to the team to convince them that DoE was practically capable to handle real problems.

7.3.1. Product Identification

It is quite difficult to determine what kind of product or assembly will be used in the first MESA experiment. Usually, on the first test there is no similar past experience that can be used as a reference. Therefore, the best choice is on the assembly/module

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3 Other cases also can be found in Hermans (2002), Jager (2004), and in appendix E.
4 This case is an extended version of the case described in Baskoro (2003)
hierarchy because the response can be measured, the module is easy to handle, and it can be detached from the product. In this case, there are available eight failed modules that can be used for the test. During the setup, a module is placed inside the test chamber and the remainder of the product is placed outside the chamber. The interface from the module to the product is done through a special conduit to avoid functionality disturbance from and to the chamber. This setting enables the module to work as in the normal product. In the first MESA test, a power amplifier module is selected. The reasons for selecting the power amplifier module are as follows:

- The field call rate of the module was higher.
- The module passed the company standard tests that had been carried out by the industrial partner using the existing methods and no failures were found. With the existing test, the industrial partner was unable to establish what went wrong with the module.
- Among all the failed modules, seven of the eight showed a breakdown on parts of the module. However, the module did operate according to the specification when tested in design and production. Therefore, the failure was suspected to be a design failure.
- The module contributes significantly to the company market share especially for Europe. Therefore, the module has significant impact to the warranty cost and customer satisfaction.

7.3.2. Define Stressor, Susceptibility of the Product

After defining the product for testing, a power amplifier module, the next step is to define the possible stressors that contribute to the failure. This process can be done using several techniques such as (1) brainstorming with the project team, (2) based on experience, and (3) other techniques. The common and straightforward method of defining stressors is using a brainstorming technique. The brainstorming technique used on this case is aimed at identifying possible stressors that relate to the suspected failure. Commonly, this exercise uses an Ishikawa diagram as shown in Figure 7.3.2. The quality of the result from this activity depends very much on the experience of the project team. Therefore, if less experienced teams perform this technique then careful attention must be given to the process. Figure 7.3.2. shows the list of possible stressors that can lead to the failure in the power amplifier module.

![Figure 7.3.2. Ishikawa Diagram of Stressor Determination for the Power Amplifier Case](image-url)
After the stressors have been defined, other factors must also be determined such as the extreme environment, its variables, and duration. During the case study, the project team selects the following extreme stressors:

- Mains failure
- Load
- Mains voltage
- Output power
- Type of Music
- Electro magnetic contamination

In other case studies the non-classical stressors such as (extreme) user is also added to the stressors list.

### 7.3.3. Preparation of the Test Equipment

To perform the test automatically, the test chamber has to be modified by adding data logging facilities and an external control system. The reason is that the standard chamber is designed to accommodate a limited number of stressors like, in this case, temperature and vibration. Therefore, provisions have to be made to accommodate for the other stressors. The modification and adjustment took quite a long time especially on combining the existing controls and additional controls into one computer control system. Since relevant timescales can vary between milliseconds (electrical events) and minutes (thermal events) problems turn out to define an efficient setup scheme especially for handling a huge database of measurement results. Generally, the preparations of the chamber can be categorized into:

- **Product**
  The preparation includes provisions for monitoring and controlling.

- **Test chamber**
  The preparation includes the chamber setup, the fixture of the module, the supply of cooling system, the supply of other systems from outside the chamber, etc.

- **Monitoring, controlling, and steering**
  The preparation includes setup the visual monitoring system, setup the control system for the test, setup data gathering system, etc.

- **Measuring Devices**
  The preparation includes setup all of the measuring system to probe the response and other measuring systems for backup.

- **Supporting Devices**
  The preparation includes safety precautions systems, and other required supporting devices.

### 7.3.4. Develop Strategy

The objective during the case is to ensure success by means of the ability to provoke failure on a module. Therefore, this case study is not yet focusing on speeding up the test. To ensure the success of provoking failure with the module, it is important to
define the test success criteria and product failure criteria. This case study uses the cycling process as a strategy, especially fixed cycle, during the test. The pattern of the cycle is determined in the test scheme. In this case, the team defines the test pattern using their experience. Below is the description of the test scheme and cycling process.

- **Test scheme**
  Test scheme is a test pattern that is used to guide the application of stressors during MESA test. In this case study, the team is able to define the limit of each stressor in a better way. However, the team is unsure of the determination of the test pattern. It is because the team defines it by means of experience. Therefore, the team is not exactly sure about the appropriate test scheme for MESA. The only consideration from the team is that the test scheme must be able to provoke the failure within short time. Therefore, the test scheme is very subjective and sometimes it can be too extreme.

- **Cycling process**
  In application, MESA will cycle the stressors according to the test scheme continuously up to a certain range of test time. There are two methods of cycling that can be used i.e. (1) fixed cycle, and (2) random cycle. In fixed cycle, the process of cycling is a repetition of one standard cycling process. Therefore, it is a predetermined process. In contrast, the cycling process in random cycle is not predetermined. In the case study, the team uses a fixed cycle so that the pattern of the cycle is predetermined. Due to the fixed cycle not all combinations of stressors are tested.

### 7.3.5. Develop a Test Plan

The necessity to develop a test plan is to ensure that the test can be smoothly performed so that it can capture as much information as possible during the test. There are two important considerations in the development of the test plan i.e. (1) Technical considerations, and (2) Cost considerations.

1. **Technical considerations**
   Technical considerations are the primary considerations in developing a test plan. They include such as setup of stressor cycle and levels, setup the measurement of the response, setup failure identification system, setup steering/controlling system for automatic test, setup data gathering system, and setup the stopping criteria for the test. It is important that these considerations are settled during the test plan development.

2. **Cost considerations**
   It should be considered that the test is not only time consuming but also involves a reasonable cost as well. Although there is no exact cost figure, it is reasonable to consider the operational cost of the chamber and other involved costs. This becomes important especially if it is planned to use MESA during the routine test scheme.

Based on these considerations, the team developed a test plan and decides to have a trial run on the chamber. The team also decides to run 40 samples of the power
amplifier modules. One may argue whether this number is sufficient for MESA to capture the failures/flaws or not. It is quite difficult to define the exact appropriate number of samples especially on the first trial. Therefore, it is reasonable to prepare as many samples as possible to ensure that the test will be able to generate failures. However, it is also important to balance between the number of samples and the cost involved. It is necessary because, in the first trial, usually the team does not know yet when or after how many cycles the failure will occur.

Table 7.3.5. describes the stressor list and the required number of levels per parameter including the duration. The levels are determined using the brainstorming technique by the technical team. Although it is not yet clear how many cycles are required until the product fails, it is expected that the level can provoke failure to appear as soon as possible. Other consideration is on the number of stressors that should be applied during the test. Looking at these stressors and their levels, it is estimated that the test will take longer time in order to complete all the combinations. This implies that another technique i.e. DoE is required to speed up the process.

In this case study, the stressor that has the longest duration in one loop is temperature (see table 7.3.5.). Temperature needs 600 seconds to perform one complete loop. In contrast, during 600 seconds, EMC has completed 60 loops because it needs 10 seconds to complete one loop. The number of loops that is required in 600 seconds for other parameters can be calculated in the same way. During the test, at least one loop of temperature has to be performed. If no sign of failure appears during this loop then the same loop is repeated for the second time and further until a failure appears. This process is done automatically using a programmable control system.

For the first pilot project, on the power amplifier module, the focus is not yet on the efficiency by means of optimum testing speed but more importantly on the effectiveness i.e. provoking and reproducing the failure. Therefore, not much attention is given on improving the test speed yet. The actual test scheme for one of the samples, in this case test 40, appears in Figure 7.3.5. The test scheme is divided into (a) standard stressors, (b) additional stressors. Standard stressors are the stressors that are included in the standard equipment. Additional stressors are the stressors that are not included in the standard equipment. Therefore, to accommodate additional stressors, the standard equipment is extended with a separate control system. The test scheme covers the detail setting and combination of the stressors during the test. The test scheme is steered and controlled using an automatic control system. The stressor levels on this test scheme can be found in appendix-B of this thesis.
As mentioned earlier, to steer and control the testing an automatic program is required. In addition, this software is used to automatically record results from the tested module. The response, in term of voltage, is measured at several points on the module. The response is also used by the software to trigger the automatic stopping system. The automatic stopping system will automatically terminate the MESA testing process if the measurement from the response is below a prescribed voltage.

7.3.6. Implementation

In this case study, the failure criteria are determined by monitoring a certain voltage in the power amplifier module. If the voltage drops to zero and remains there this is an indication that the power amplifier module has failed. The response from the voltage is sampled and recorded in the database. Results from 40 tests show that 3 modules have the same type of failure (left amplifier channel). Two of those three modules, tests on sample 29 and sample 40, failed at almost the same test time. Although the third module has the same failure, at left amplifier channel, it occurred...
at different time than the other two modules, meaning a different combination of stressor levels. Therefore, the third module is disregarded and it is not used for further analysis. The module on test 29 fails 2:56 minutes after the test and module on test 40 fails 2:55 after the test. The graph of these modules appears as in figure 7.3.6.

7.3.7. Validation

As mentioned in section 6.4.3., the result of a test is considered valid if it can be replicated. Therefore, during this case, repeating the test with the same test scheme will perform the validation. In the validation process, if the module fails at around the same time as the previous failure then the result is considered valid. This case study will not try to reproduce the failure because it is considered acceptable and valid if the result can be repeated with the same test scheme. Therefore, during this case study, the validation is done by comparing the failed modules that have similar type of failure.

Two modules of test 29 and test 40 are compared. Figure 7.3.6. shows that these modules have different patterns on each measuring parameter including especially on the voltage at left amplifier channel (VCC\_left). VCC\_left is used as an indication of failure from the modules especially if the voltage drops to zero. Figures 7.3.6. also demonstrates that although the pattern of VCC\_left at modules on test 29 and test 40 are different, VCC\_left drops to zero at almost the same time. Therefore, the result of this comparison can be used as the validation of the test on the power amplifier module.

7.3.8. Analysis and Verification

The power amplifier module breaks down at a certain time that is indicated by the output voltage of the left amplifier channel, VCC\_left on figure 7.3.6., goes to zero and remains there. The failure found on VCC\_left is the result from the stressors applied during the MESA test. Moreover, this finding leads to the question whether this failure can be repeated or not. It is because if the failure can be reproduced, then it is argued that those stressors contribute to the failure and therefore further analysis, for example root-cause analysis, can be done.

Further tests on other power amplifier modules using the same test scheme ends up with the same failure. Figure 7.3.6., in test 40, shows that the same failure appears again almost at the same time. The next question is what kind of stressors and at what level that provoke the failure? To answer this question, it is required a technique that is able to search, and to identify the significant stressors. However, the first pilot test is not intended to define the significant stressors because the purpose of the first test is only to provoke and to replicate the failure. Theoretically, the dominant stressors that cause the failure can also be defined by observing from the type of failure. However, identifying the dominant stressors using this technique requires some degree of knowledge and experience. Although it may possible, in most cases, it is not easy to be done. Therefore, other technique such as DoE can also be a solution.

There are also other ways to define the possible (dominant) stressors that provoke the failure. Instead of observing the failure, the possible (dominant) stressors that provoke
the failure can also be identified by analyzing the stressor scheme at the point when the failure occurs. For example, in figure 7.3.6., the failure is indicated when measurement on VCC_left suddenly drops to zero at some point in time. If using this time as a point of reference, then the suspected (dominant) stressors can be defined from figure 7.3.5. In figure 7.3.5., at the time when VCC_left drops to zero, each stressor stops at a certain level. Therefore, the suspected (dominant) stressors can be defined by looking at the stressors that stop at the highest level. In this case, in figure 7.3.5., load and mains voltage are at the stressors that stop at the highest level when the failure occurs. Other stressors that are on the low level are expected to have less contribution to the failure of the module in this case.

7.4. How to Improve Efficiency

In general, one of the purposes of any DoE technique is to reduce the number of experiments from the available factors. In practice, there are available many DoE techniques. Therefore, a guideline to choose a DoE technique is needed. This thesis uses the guideline by Schmidt and Launsby (1977) as a method to choose a DoE technique (see also appendix A).

7.4.1. The importance of using DoE

An example of the importance of using a DoE technique is illustrated using the first case study. During this research, the first case study accommodated 8 factors or stressors for the test. If using the common DoE technique such as full factorial for 8 factors with two levels then it requires $2^8$ experiments or 256 experiments for each product sample. The number of experiments will be higher if using more than 2 levels. For example, for 8 factors with three levels then it requires $3^8$ experiments or 6561 experiments for each product sample. However, this number of experiments can be reduced such as by using a fractional factorial design. For example, if using a $L_{12}$ Taguchi fractional factorial or Placket-Burman with two levels for 11 factors then it requires only 12 experiments. Refer to the case study, the team has already picked up 8 possible factors for the experiments. Therefore, it requires additional 3 more factors in order to meet the experiment design using Placket-Burman technique. To complete 11 factors, the team picks up additional 3 suspected stressors related to the failure. The advantage of using more stressors is that, as mentioned earlier in section 6.4.2.1., it enables MESA to find the searched failure with high possibility of success.

Although full factorial requires 256 experiments, this DoE technique is considered better than using the classical test combination performed on this case. It is because the full factorial is not only known as a familiar DoE technique but also most of DoE software accommodates it as a standard package. The disadvantage of using full factorial is that it requires a lot of experiments. For this reason, to enable the experiment to be manageable, the number of factors that is used in full factorial must be reduced. In contrast, section 6.4.2.1. and 7.3.3. suggest that to ensure high quality of result MESA must accommodate a large number of factors. Although it sounds contradicting, this is still possible to be done if using a DoE technique such as the fractional factorial for the experiment. It is because the fractional factorial enables to accommodate more factors with less experiment. Therefore it can accommodate the constraints that are described in section 6.4.2.1. For comparison, in this case study MESA required, according to the calculation, around 768 hours to test all possible stressor combinations using traditional technique (Hermans, 2002).
7.4.2. The obstacles

Although theoretically DoE can be applied in MESA, in practice it requires adjustment and adaptation. The major obstacle that makes DoE to be difficult is that DoE could only perform static experiments (see section 6.2.3.). In contrast, MESA test also can be used in a dynamic mode. In dynamic mode, MESA can apply the stressors on a continuous cycling process until the product fails.

Considering the obstacles, the team then decided not to apply DoE on this case study yet. Although in this case study the team is able to provoke the failure effectively with acceptable result, it is considered not yet efficient. Regardless the scientific acceptability and the accurate result of DoE, therefore adopting DoE in MESA requires more than understanding of its technique. The adoption of DoE in practice is mostly inhibited by non technical factors. Therefore, the challenges on this research are both on technical and non technical issues.

7.5. Case Summary of MESA

During the MESA case study six cases have been carried out with various objectives. Instead of discussing all the cases one-by-one, this section presents the summary. A short description of the cases can be found in appendix E of this thesis. The general summary of the case result during the MESA case study is presented in table 7.5. The complete version of table 7.5. can be found in appendix F of this thesis. Moreover, the detailed report of the cases is also available in the master thesis of Hermans (2002), and Jager (2004). Table 7.5. is divided into several columns. Each column contains a specific explanation for the corresponding case. Each column is explained as follows:

Table 7.5. General Summary of MESA Test Cases
(For clarity see the complete version in appendix F)

<table>
<thead>
<tr>
<th>No.</th>
<th>Module</th>
<th>Product Characteristic (Electrical or Mechanical)</th>
<th>Prior Failure Mechanism</th>
<th>Phase in Roller coaster</th>
<th>Phase of Product in product life cycle</th>
<th>Failure Found</th>
<th>Replicability</th>
<th>Reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power 4 Electrical</td>
<td>Known</td>
<td>2</td>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3DTC Both</td>
<td>Known</td>
<td>2</td>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5DTC Both</td>
<td>Unknown</td>
<td>1+2</td>
<td>P</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>6ch Amp Electrical</td>
<td>Unknown</td>
<td>1+2</td>
<td>Dev</td>
<td>No</td>
<td>?</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>DVD625 Both</td>
<td>Unknown</td>
<td>1+2</td>
<td>F</td>
<td>No</td>
<td>n.a.</td>
<td>n.a.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>AV2 Both</td>
<td>Known</td>
<td>2</td>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

Note: D = Design
Dev = Development
PP = Pilot Production
P = Production
R = Product return
= Reliable test

1. No
This column indicates the number of the case that is performed during the MESA case study. Therefore, case no. 1 indicates the first case and case no. 6 indicates the last case that is performed during this research.

2. Module
This column indicates the type of module that has been tested

3. Product Characteristic (Electrical or Mechanical)
This column indicates the characteristic of the module. Usually, a module can be categorized into (1) electrical, (2) mechanical, or (3) both, combination of electrical and mechanical.
   Although this is not available in table 7.5., it appears in appendix F. This column indicates the reason of testing the module.

5. **Prior failure mechanism**
   This column indicates the knowledge of previous failure mechanisms related to the module.

6. **Type of failure/defect (Appear in appendix F)**
   Although this is not available in table 7.5., it appears in appendix F. This column indicates the type of failure/defect that occurs on the module.

7. **Phase in rollercoaster**
   This column indicates the categorization of the failure in the four-phase rollercoaster model (phase 1 to 4).

8. **Phase of product in PDP**
   This column indicates the location of the product/module in the product lifecycle.

9. **Failure Found**
   This column indicates the result of the test. It shows whether the failure is found or not found after the module is tested.

10. **Repeatability**
    This column indicates the method of validation. It shows whether the result is repeatable or not.

11. **Reproducibility**
    This column indicates the method of validation. It shows whether the result is reproducible or not.

The results during the MESA case study have shown that failures can be found, in particularly, when the failure mechanism is previously known. By knowing the failure mechanism the determination of stressors becomes more predictable. Moreover, the applied stressors are also closely related to the failure mode. If the failure mechanism is known, then MESA can be used to define the dominant stressors that cause the failure and to validate the result.

The goal of developing MESA, as mentioned in the previous chapter, is to improve the effectiveness of the most recent test concept. In practice, in order to realize the goal, MESA must be able to surface the failure, define dominant stressors, and validate the results (product, assy., module, or. etc.). In addition, MESA must be able to do it in a situation where the failure mechanism is previously known or unknown. It is called a black box problem if the failure mechanism is unknown. Commonly, in the black box problem it opens room for guessing. The difficulties in a black box problem are on the determination of stressors, the stressor setup, and the failure identification. For example, although the chosen stressors are already correct, if the level of these stressors is too low then the test will find no failure. Another example is that the test must be aborted because it consumes a lot of time before finding any failure. This can happen because (1) the stressors and their combination are unrelated with the failure, and (2) the level of these stressors is also incorrect. On the black box problem, the important indicator of success is finding a failure and validating it. Only one case, the case number 3 in table 7.5. i.e. the 5-DTC module, out of three black box problems, the cases number 3, 4, and 5, during the case study is considered successful in finding and validating the failure. The case of 5 DTC module demonstrated that MESA is able to surface failure from a product with unknown failure mechanisms.
7.6. General Evaluation

On achieving the objective of MESA, several important non-technical issues are necessary to be addressed. Improving on these issues will increase the likelihood of success. The related issues are:

- **Clear goal**
  The goal of MESA test has to be clearly defined, so that the test plan can be clearly developed. It is suggested that the goal should be specific, measurable, achievable, realistic, and time bounded.

- **Team Brainstorming**
  Most of the test plan development requires prior knowledge of the product and its failures from other similar products. Therefore, it is necessary to accommodate experts' opinion from the related fields when performing brainstorming. Their expertise helps to improve the determination of the test plan so that the judgment will be closely related with real practical problems.

- **Communication**
  The project leader must communicate effectively and clearly to the team members. This will help reducing unanticipated problems during the development and execution of the test.

- **Documentation**
  Documentation plays a significant role not only during the test but also after the test. For instance, in the validation phase, to perform repeatability of the test with the same scheme depends on how the previous test has been documented. The same thing also happens during reproducing the failure after a certain period of time. The success of the validation depends on how good the documentation has been done.

Other important factors that require attention are as follows:

- **Specimen Determination**
  Another important issue related to the success of MESA is on the determination of the specimen for testing. Although it is possible to do MESA test on the whole product, it is suggested to avoid using a product as specimen. The problems of using a product as a specimen are on the difficulty to search the causes of the failure and on the difficulty to define the sources of the failure. In theory, it is possible to choose the specimen from e.g. component, sub-assembly, assembly, module, and product. However, it is advised to choose the lowest level from the product hierarchy as the specimen. For example, if testing on component level is not possible then there is possibility to perform testing on sub-assembly, assembly, or module, and the last choice is on the product. The argument of narrowing down the sources of specimen from the product hierarchy is to avoid other sources of failure that are not related to the problem. It is because during the test there is a possibility that other unrelated sources can influence the searched failure. Naturally, in a product hierarchy the weak part will break down earlier than the stronger one.
Therefore if the problem, that is investigated using this test, is stronger than the other part in the product, the other part will be broken before the real problem is captured. Therefore, the test will not find the real problem because the weakest part on the specimen has already failed.

- Prior product knowledge
  Table 7.5. shows the summary of the MESA case study performed during the research. This table shows the overview of the MESA performance, strength and weaknesses, during its development. One important point on the success of MESA test is prior knowledge of the product. The table shows that the success of MESA, by means of replicability, is mostly because the team has prior knowledge of the product. Having prior knowledge of the product can reduce possible guessing during the test.

- Shifting focus to Pre-test and Post test
  It is also important to notice that to achieve faster test results requires better (1) test preparation, (2) test execution, and (3) result analysis. Normally, in test execution, there is limited available time. Moreover, to ensure the success during test execution, the test must be performed with the highest possible of engineering standards. Therefore, focus has to be given to the pre-test activities because performing high quality pre-test activities will ensure success on the later processes.

7.7. Contradictions in MESA

The strategy used in this case study is to reduce the complexity of dynamic systems by reducing large numbers of stressors into a small manageable stressor set. This strategy is useful if the objective is only on achieving the efficiency. However, to achieve the effectiveness, a different strategy must be applied and mostly in contradiction with the strategy to achieve efficiency. As indicated in chapter 6 that MESA is developed to improve the effectiveness of the current test concept and to maintain similar efficiency performance. Therefore, MESA must apply different strategy than the strategy applied in this case study. Instead of reducing large number of stressors, the strategy to achieve effectiveness is to apply large stressor sets. The reason is that to cover failure mechanism requires large dimension of the stressor set. Consequently, using the classical concept of testing with a large stressor set will consume enormous test time. Therefore, to achieve the effectiveness while maintaining the efficiency requires a technique that can perform tests with a large number of stressors in an efficient manner.

For this reason, one approach is to apply the non classical DoE technique such as fractional factorial. The reason is that this technique enables to use a large stressor set with less experiments and therefore less time. The other approach is not to test until the failure emerges as in the classical way but to test only until the sign of failure is identified. This is possible only if there is capability to identify the fault or the sign of the failure. However, applying this strategy requires further research especially on the way of aligning DoE into dynamic tests because the nature of DoE is a static experiment. Further discussion appears on chapter 8 as a suggestion for future research.
This chapter is the last discussion of the overall research on this thesis. The next chapter, chapter 8, will conclude this research by answering all the research questions. The next chapter also presents the strength and weaknesses of MESA in real application. Furthermore, chapter 8 will end with presenting the possible opportunities for future research.
CHAPTER 8. CONCLUSION AND FUTURE RESEARCH

The main purpose of this chapter is to present the conclusions from this research and to suggest directions for future research. The conclusions discussed in this chapter cover both an academic and an industrial viewpoint. The academic viewpoint discusses if- and how- the research questions, presented earlier in this thesis, were answered. The industrial viewpoint discusses the experiences with the industrial application of MESA.

The aim of this research is to provide a contribution to proactive efforts of preventing reliability problems by developing an alternative-testing concept. This thesis focuses especially on so called "early failure" (class 1 and/or class 2 failures in the four-phase rollercoaster model) as defined in section 3.6. For this goal research questions (section 3.7.) are established. This chapter also discusses the proposed alternative test concept of which the development has been presented in earlier chapters and that was tested in several industrial test cases.

8.1. Overview of the Research

Securing a reliable product before it is launched into the market is an important goal for companies active in new product development. In order to ensure reliable products, this thesis analyses two methods: (1) the traditional method of reliability testing during the back-end process, and (2) an alternative method, developed in this thesis, that aims at ensuring product reliability during the front-end process.

This thesis demonstrates that, although using the developed alternative method is conceptually more complicated, there are considerable advantages in ensuring product reliability during early phases of product development. Testing in the early phases introduces, however, a new set of problems related to the higher level of uncertainty that is inherent in the earlier phases of product development. It requires the analysis of far larger numbers of potential failure mechanisms with a corresponding even higher number of influencing parameters. Since this thesis aims at developing a test-strategy that realistically fits in modern product development processes, this thesis focuses especially on failure mechanisms with a large number of parameters involved (high dimensionality). It focuses on class 1 and/or class 2 failures in the four-phase rollercoaster model, since especially these failures are difficult to analyze in traditional testing concepts. As indicated more in detail in section 3.6., the objective of this research is to develop a new testing concept that can be used for identification and/or elimination of class 1 and/or class 2, time independent hard reliability
problems, in the early PDP. The research objective is decomposed into two research questions (see section 3.7.).

1. Do the class 1 and/or class 2 failures, time independent hard NFF problems, in the context of the four-phase rollercoaster model exist?

2. Is it possible to identify, and prevent class 1 and 2 hard reliability problems in the early product development process?

This thesis confirms in chapter 4, the existence of class 1 and/or class 2 failures in industrial products. Although class 1 and/or class 2 failures can exist, it is not easy to (proactively!) identify them. Therefore a strategy was developed to identify class 1 failures and, especially the more difficult to analyze, class 2 failures based on the Q&R reference model developed by Brombacher et al. (2005). This model describes, with respect to early failures, two classes of failures: hard failures and soft failures. It was also found that the Q&R model can be used not only to identify and classify failures, but that it can also be used to guide the development of a new test concept to focus on the time independent hard reliability problems.

As addressed in chapter 2, time independent hard reliability problems are problems that usually occur during the first phases customers use the product. Due to the potentially large number of parameters involved, class 1 and/or class 2 failures cannot be easily identified by manufacturers. Therefore, these types of problems require a special test concept to identify them. Generally, early reliability problems appear in a mix of product problems commonly described as Dead on Arrival (DOA) and/or NFF (No Fault Found) (see also section 4.3.1.). Among all problems, NFF is the biggest portion from the problems faced by industries (see also chapter 4). To extract time independent hard reliability problems from the NFF can be done by splitting the NFF into different sub-classes. In this thesis, NFF is decomposed into hard failures and soft failures. Hard failure is then split into time independent problems and time dependent problems. For this purpose the Q&R reference model, described in section 2.4.3., and 2.4.4., is used.

The aim of this thesis is not only to identify these failures but also (research question 2) to develop a method to prevent hard reliability problems in the early phases of the PDP. To achieve this objective, the thesis develops a new test method: Multiple Environment Stress Analysis (MESA). This thesis has split the development of MESA into two steps; the first step focuses on the concept, and the second step focuses on the application. The first step is performed to identify failure mechanisms that are previously unknown and to identify the corresponding dominant stressors. After that, the second step of MESA attempts to use MESA in the early PDP. To reduce risks it was necessary to develop knowledge, on the first step, and build up confidence on MESA before attempting to use it in early PDP.

The results of the first step show that MESA has the potential to handle problems where the failure mechanism is previously unknown. In this research, cases of MESA were categorized as (1) cases on problems where the failure mechanism is previously known, and (2) cases on problems where the failure mechanism is previously unknown (black-box problems). This research demonstrates, within limited cases, that MESA is able to find failures (in a significant number) on all cases where the failure
mechanism is previously known. However, MESA can only find partial failures from cases where the failure mechanism is previously unknown. The results from the second step can only be considered from a narrow viewpoint. It is because during this MESA case study, in the second step, only a limited number of products were available for testing.

This thesis demonstrates that this research has provided an alternative way of preventing hard reliability problems. This research also demonstrates that MESA can be used as an alternative test concept in order to surface the early failure, class 1 and/or class 2 failures of the four-phase rollercoaster model, hard reliability problems during the testing of a (new) product. Therefore, this research provides an alternative (accelerated) test concept besides the available (accelerated) testing concepts. The following section presents the conclusions of the research.

8.2. Conclusion

The objectives of developing MESA are to compensate the limitations of the current testing concepts in terms of efficiency, effectiveness, and suitability of implementation within the constraints of the early PDP (see general assessment in chapter 5).

8.2.1. Efficiency

Assessment of the current testing concepts, such as highly accelerated test concepts, concludes that the test concepts are already efficient because the speed of the test is already suitable. Achievement of a suitable test is possible because highly accelerated test concepts accommodate cycling techniques with multiple environment stressors during the test. Although this is an advantage for highly accelerated test concepts, the disadvantage is that highly accelerated test concepts can cover only limited stressor sets (see section 5.5.1.).

MESA accommodates several techniques to achieve suitable test speed. Among other techniques that have been discussed in chapter 6, MESA also accommodates cycling techniques as in the highly accelerated test concept. Therefore, MESA is able to accommodate more stressors other than only the environment stressors. MESA is able to accommodate both traditional and non-traditional stressors. As a result, MESA is able to handle large stressor sets using a similar test chamber as in highly accelerated tests. Mainly, the improvements that have been made in MESA cover the test concept. To effectively improve the test concept, the equipment also requires some adjustments such as by adding a new control system. The main improvement on the test concept is done by (a) using the concept of engineering test, (b) migrating more activities in pre-test phase, (c) using more accurate determination in defining stressors type, setting, and scheme, (d) introducing DoE. These improvements enable MESA to accommodate large stressor sets with limited experiments so that it can maintain a similar test speed as in the current test concepts.

8.2.2. Effectiveness

Chapter 5 shows that, when applied in an industrial context, the effectiveness of the accelerated test concept requires considerable improvement. Among them, the major points of improvement must be given to the test so that it can focus on early failure hard reliability problems and to use large numbers of stressors to cover potential
failure mechanisms. Therefore, to improve the effectiveness MESA uses the strategies of (1) testing on large coverage, and (2) integrating DoE into MESA to enable accommodating a large number of stressors. These strategies align with requirements that have been defined in section 6.3.1.

The main concern on the effectiveness is the ability to provoke hard reliability problems. Table 7.5. shows that all cases deal with reliability problems categorized in class 1 and/or class 2 failures of the four-phase rollercoaster model. Table 7.5. shows that the failure, early failure hard reliability problems, has been found in 4 cases (out of total 6 cases) during the test. Therefore, this thesis shows that MESA is an effective test.

8.2.3. Position of MESA in PDP

Although ideally the position to apply MESA is in the front-end PDP, in an industrial environment it requires adjustment in order to align with other existing testing methods. As defined earlier, section 2.2.1., front-end phases are the phases before production. Therefore, MESA is expected to perform before the production process. Although MESA is designed for front-end phases, MESA still has considerable added value when applied in back-end phases. It is because technically MESA can also be used as a verification/validation test method and help on problem root-cause analysis.

8.3. Implementation of MESA in Industrial Context

It is considered not yet the time to conclude the implementation of MESA in industrial context because MESA needs to be tested in more cases. However, this section tries to argue on some points that have been observed during the development and pilot testing of MESA.

8.3.1. Method

The success of MESA as an engineering test method is dependent upon engineers’ expertise. The observation during MESA development shows that MESA requires a broad extensive engineering expertise to ensure high standard quality of MESA. It is also not surprising that every MESA case will require different adjustment on the test scheme because the problems are different on each case. For MESA, the necessary engineering expertise is product knowledge and test equipment knowledge. In addition to expertise in product knowledge and test equipment knowledge, it is also observed during the case study that it is useful to have expertise in automatic control systems as part of the engineering expertise. This know-how was available in the company where the case studies have been performed. It is advised that this know-how must be preserved because it is needed at any time when performing MESA.

8.3.2. Some notes on industrial application of MESA

The important constraints of MESA application in an industrial context are technical infrastructure and operational costs. To ensure the success of the test and reduce costs, this thesis proposes the migration of more activities into pre-test phase and to develop a more pro-active and more comprehensive test plan.

A more important consideration of MESA operation is on the quality of results that is the ability to surface class 1 and/or class 2 failures and the ability to define the main
factors that create them. Although MESA can be used, technically, as a validation test, the main purpose of MESA is to be used as an analysis test (see section 5.1.2.2). In the MESA analysis test, the main objective is to analyze the root cause of known failures. Since MESA concentrates on a detailed analysis of (the root causes of-) conceptually known failure mechanisms, it requires a solid knowledge of these failure mechanisms including their context. In order to obtain the required information a team will have to be assembled with people from diverse technical backgrounds. The ideal team will be the cross functional team that is composed by people in various related departments such as development, quality, production, sales/marketing, and others that deal with the product. The cross functional team is necessary because diverse knowledge and experience from the team can help on making a comprehensive assessment on the product failure and root cause analysis. It is expected that, by using a cross-functional team, the problem assessment and root cause analysis can be done with better result.

8.4. Future Research

This thesis has observed some interesting topics to be explored in relation to class 1 and/or class 2 failures of the four-phase rollercoaster model such as soft reliability problems. It is because problems on a product are not merely hard reliability problems. It is not surprisingly that a product failure is also created by soft reliability problems. However, to limit the scope, this thesis will only suggest future research based on MESA. Some important points that have been observed during the entire period of the research with industrial partner are as follows.

Sources of weaker products
As indicated earlier that one method to create failure is by changing the factor of susceptibility. However, during this research, this strategy is not used. Therefore, it is suggested for future research to explore the possibility to apply this additional strategy. Especially, understanding of the weakening process of a, statistically speaking, extreme (weak) product that is taken from products beyond the control limit in the production process could create added value.

Adopting expert system in MESA
The development of an expert system helping on all aspects of MESA could be a next step for further research. Such a system should assist in establishing the dominant stressor sets and in selecting the DoE design and performing DoE related analyses. Such a system would reduce the experience required and prevent errors when performing MESA.

Integration of MESA into existing front-end testing methods
Due to limitation in time and number of cases, this research was unable to test the possibility to integrate MESA with existing tests that are performed in the front-end phases of the PDP. Therefore, it is advised to further explore on this direction by integrating MESA with testing methods that are performed at the front-end phases of the PDP.
GUIDELINE FOR CHOOSING DOE STATEMENT OF THE PROBLEM & OBJECTIVE

DETERMINE WHAT TO MEASURE & COMPLETE

3

2

3

HOW MANY LEVELS FOR EACH FACTOR?

6 <= K <= 11

K <= 4

FULL FACTORIAL
K=2...n reps >= 9
K=3... n reps >=5
K=4...n reps >=3

K = 5
2^5-1
½ Fraction
N reps >=3

PLACKET-BURMAN OR TAGUCHI L12
SCREENING
N reps >=4

FULL FACTORIAL
K=2...n reps >= 7
K=3... n reps >=3

K <= 3

HOW MANY FACTORS (K)?

K <= 7

Screening

MODELING

K <= 5

6 <= K <= 7

N reps >=4

CENTRAL COMPOSITE or BOX-BEHNKEN DESIGN
K=2...n reps >= 9 (CCD)
K=3... n reps >=5 (CCD or BB)
K=4...n reps >=3 (CCD or BB)
K=5...n reps >=3 (CCD)

NOT ALL QUANTITATIVE (at least 1 Qual.)

TAGUCHI L18 SCREENING
(include 2 level factor)
N reps >=4

K <= 7

N reps >=3

K <= 5

N reps >=3

K <= 4

6 <= K <= 11

K = 5
2^5-1
½ Fraction
N reps >=3

PLACKET-BURMAN OR TAGUCHI L12
SCREENING
N reps >=4

FULL FACTORIAL
K=2...n reps >= 7
K=3... n reps >=3

K <= 3

HOW MANY FACTORS (K)?

K <= 7

Screening

MODELING

K <= 5

6 <= K <= 7

N reps >=4

CENTRAL COMPOSITE or BOX-BEHNKEN DESIGN
K=2...n reps >= 9 (CCD)
K=3... n reps >=5 (CCD or BB)
K=4...n reps >=3 (CCD or BB)
K=5...n reps >=3 (CCD)

Adopted from Schmidt, and Launsby (1977)
## Appendix B

### Stressors setting and duration for power amplifier module

**A = Temperature**

1. Low Limit  -20°C  200 sec  
2. Normal Limit +20°C  200 sec  
3. High Limit  +70°C  200 sec  

**B = Mains Failure**

Set-up Phase free  
Spikes with +/- 1500V and +/- 2500 V  
1. Mains Failure off  2 sec  
2. + 1500 V  2 sec  
3. - 1500 V  2 sec  
4. + 2500 V  2 sec  
5. - 2500 V  2 sec  

**C = Vibration**

1. Low Limit  0 G  200 sec  
2. High Limit  50 G  200 sec  

**D = Load**

1. Nix Speaker (Dummy)  
2. 2 Speaker Series  12 Ohm  10 sec  
3. Speaker Leads  10 meters  10 sec  
4. 2 Speakers Parallel  3 Ohm  10 sec  
5. Resistor  6 Ohm  10 sec  
6. Hi – End Speaker  6 Ohm  10 sec  
7. Cheap Speaker  6 Ohm  10 sec  
8. Original Speaker  6 Ohm  10 sec  

**E = Mains Voltage**

Test to the technical limit and then +10% in direction to specification  
1. Low Technical Limit  +10%  30 sec  
2. High Technical Limit  -10%  30 sec  
3. Specification Value  30 sec  
4. Mains Interruption  100%  50 msec  

**F = Output Power**

1. 50 mW  10 sec  
2. 0,7% THD  10 sec  
3. 10% THD  10 sec  

• THD = Total Harmonic Distortion  

**G = Music**

10 sec parts of significant music parts of different music style  
1. Heavy Metal  60 sec  
2. Rave  60 sec  
3. Classic  60 sec  
4. IEC 628 Noise  60 sec
Appendix C

Figure 7.3.5. Actual Test Scheme for Power Amplifier Module

(a) Standard Stressors

(b) Additional Stressors
Figure 7.3.6. Test Results Showing Replication of Failure

Test 29

Test 40

Fail

Fail
Appendix E
Additional Case Studies

This appendix summarizes the cases that have not been discussed in the main text of this thesis.

E.1. 3DTC Module

1. Product Identification
   a. Module Name:
      3DTC
   b. Module Characteristic:
      3DTC is a 3 disk tray changers. This module is a disk tray changer that is able to change 3 compact disks by using three trays.
   c. Problems:
      The field problem of the 3DTC is that the trays are trapped in the changer and it is difficult to repair.

2. Reasons for Testing
   The aim of this test is to reproduce the failure that occurred in the field so that the causes of failure can be defined.

3. Test Execution:
   a. Define stressors
      After analyzing the problems the test team defines list of stressors to be applied during the test. Beside the classical stressors the team adds also the non-classical stressors of customer usage into the following list.

      1. Non-classical stressors:
         • Customer usage
      2. Classical stressors:
         • Temperature
         • Vibration
         • Mains failure
         • Mains voltage

      The team also makes some adjustments on the standard test equipment in order to accommodate all stressors.

   b. Defining test scheme
      In this test, the team defines test scheme based on experience.

   c. Setting up the module on the equipment
      The module is setup inside the test equipment while the main part of the product is placed outside the chamber. This is to ensure that the test will only affect to the module itself. Moreover, the stressors are programmed by a computer that is connected with the main part of the product. Using this system enables to steer the programmable stressors, especially the customer usage, automatically.
d. Failure criteria
In this test, it is not possible to define the failure by means of measuring a response. Therefore, the team decides to use visual observation in order to detect the failure. The visual observation is done by recording the event of testing using video camera. The test is stopped when the tray malfunctions.

4. Result
Seven tests have been done and all of them show problems on the tray. Two tests show a weak construction of the tray and five tests show problems on the gear of the tray.

5. Discussion
The results of the test show that the field problem can be reproduced during the test. However, it is difficult to define the precise time when the failure occurs. It is because instead of measuring the response from the tray, this test observes the failure visually using video camera. Therefore, it is difficult to define precisely the time when the failure occurs.

There are several reasons that may cause the gear problem and the weakness of the construction from the tray. However, the main point is that the team has used MESA test to replicate the failure. Therefore, the team can make an improvement on the tray. Moreover, if necessary, the team can perform a similar test to see the effectiveness of the improvement.
E.2. A DVD Set

1. **Product Identification**
   a. Module Name:
      DVD
   b. Module Characteristic:
      A complete set of a DVD.
   c. Problems:
      No specific problem

2. **Reasons for Testing**
   To test the robustness of the product

3. **Test Execution:**
   a. Define stressors
      The stressors to be applied during the test cover both classical and non-classical stressors. The non-classical stressor is customer usage and the classical stressors almost similar to other cases. The following is the list of the stressors.
      
      1. Non-classical stressor:
         - Customer usage
      2. Classical stressors:
         - Temperature
         - Vibration
         - Mains interference
         - Mains voltage
         - Mains interruption

      To accommodate the stressors, especially the non-classical stressor, the team makes some adjustments on the standard test equipment.

   b. Defining test scheme
      In this test, the team also defines the test scheme based on experience. The important consideration on the test scheme determination is that the test scheme should be designed to be able to generate high severity on the product. It is expected that higher severity can provoke failure on the product. Therefore, if a test scheme gives no impact on the product then the team will change the test scheme to be a more severe test scheme. This will be done several times until the test can find a failure or if the test finds no failure then the team must have confidence that the product is robust.

   c. Setting up the module inside the test equipment
      The DVD set is placed inside the test equipment while the set is connected to a TV that is placed outside the chamber. In the DVD, inside the camber, several measuring devices are placed. They are to measure temperature and vibration in various locations inside the DVD. The temperature measurement is placed on the MPEG board at voltage regulator, main IC, Power supply transformer, Case
temperature, and inside air temperature of the DVD case. The vibration measurement is placed inside the DVD at the middle location.

d. Failure criteria
In this test, the failure criteria are defined by observing the appearances on the TV monitor that is placed outside the chamber. Therefore, there is no specific failure criteria has been set. In normal condition, the TV monitor shows a normal appearance when the DVD plays a certain movie. Logically, if the DVD has some problems when playing a movie on a tested condition then the TV monitor is expected to show some disturbances. This failure criterion has been defined in this test.

4. Result
Several runs have been performed during the test with different test schemes. The result shows that in all runs the monitor shows no indication of failure in the DVD. Therefore, the team concludes that the DVD is robust.

5. Discussion
The analysis consists of (1) several setup runs and (2) analysis runs. In the setup runs the starting values for the stressors are determined. In setup runs, only one stressor at a time is applied. The starting values on the setup runs are as follows:

- Temperature cycling:
  4 minutes on 100 degrees Celsius followed by 3 minutes on -20 degrees Celsius.
- Vibration:
  In each temperature interval 2 minutes vibration of 10 GRMS is applied. During setup the product was able to read the contents of the DVD with this load applied.
- Mains voltage:
  The mains voltage is varied between 80 Volts and 265 Volts with a duration time of 30 seconds.
- Mains interference:
  Each two seconds there is a mains interference of 1000 Volts asynchronous with 10 ns and a mains interference of 2000 Volts asynchronous with 10 ns. During these two seconds also a polarity change takes place.
- Mains interruption:
  As from the third run the mains voltage was interrupted for about 500 ms each minute. Because of this the player switched to standby mode.

It is encountered, in one of the setup runs, a software hang-up. In addition, at a certain time the monitor shows some disturbance. Moreover, the display on the player shows no reading. However, the voltage readings show that the player is still running. However, after some adjustment on the power supply the player operates normally. Therefore, this failure is indicated as a soft, non-critical failure. This failure occurs only once.

The analysis runs is done by analyzing the temperature performance. After 2 hours of analyzing the lower temperature, the temperature set is changed to -10 degrees Celsius to establish a higher average temperature. However, after 8 hours of monitoring the
performance of the DVD, there is no sign of a failure. Therefore, the analysis runs is stopped.

The second analysis run is performed because no failure has been found in the first runs. For this reason, the stressors scheme is changed with the following configuration.

- **Temperature cycling:**
  The temperature intervals will be changed to 6 minutes each. The goal is to increase the difference between minimum and maximum temperature.
- **Vibration:**
  The vibration intervals will be doubled. The vibration intensity will be set to 15GRMS. Possibly this will invoke other mechanisms in the product because it won’t be able to read the DVD at 15 GRMS vibration according to specification, but should be able to read when the vibration is stopped.
- **Mains interruption:**
  The mains interruption minimum will be lowered to 0 Volt and the maximum to 2500 Volt.
- **Mains voltage:**
  The mains voltage lower limit will be lowered to 60 Volt.

With these changes still no failures are found. Therefore it is decided to change the stressors to the maximum ability of the test equipment. In addition, the team considers adding mains interruption as a stressor. To maximize the impact of the temperature cycling the cover was left off. The changed stressors were:

- **Temperature cycling:**
  6 minutes on 100 degrees Celsius followed by 6 minutes on 0 degrees Celsius.
- **Vibration:**
  In each 2 minutes temperature interval, vibration of 40 GRMS is applied.
- **Mains voltage:**
  It is varied between 60 and 265 Volts with 30 seconds duration.
- **Mains interference:**
  Every two seconds, there is a mains interference of 2500 Volts asynchronous with 10 ns. In addition, during two seconds, a polarity change takes place.

Although the stressors scheme has been changed to maximize the impact, the player still operates normally. During the test, with several changes in stressors scheme, there is still no failure appears on the product. Therefore, it is concluded that the DVD is robust.

There are two possibilities that create no-failure on the product. They are (1) the method that is used to observe failure is too global, and (2) the stressors are unable to provoke failure. The explanation for the first possibility is that using visual observation via a monitor to detect a problem in the DVD may not be correct. The reason is that not all technical failures occurring in the DVD lead to a picture disturbance that can be observed via a monitor. Therefore, instead of directly observing the picture via a monitor, it is possible that failures can only be observed by measuring the technical performance. The explanation for the second possibility is
that the stressors are unable to provoke failures that lead to a picture disturbance. The possible reasons are (1) the stressors level is low or (2) the stressors type and combination are wrong.
E.3. AV2 Module

1. Product Identification
   a. Module Name:
      AV2
   b. Module Characteristic:
      AV2 is an optical drive in a DVD. An AV2 module includes at least the loader, OPU (optical pickup unit), servo controller, and channel CODEC. The characteristic of the AV2 is that this module can play DVD, record to DVD+R/RW media, and play all CD format but AV2 is unable to record to a CD. This module is intended specially for a DVD video recorder.
   c. Problems:
      This module has experienced a decreasing amount of light that lands on the detector. The problem is detected by measuring the beam landing. It is suspected by the team that the glue that holds the mirror is the main problem.

2. Reasons for Testing
   The aim of this test is to check the difference between aged and non-aged glue to the performance of AV2. The aged glue is a treatment on the glue, hardening process using an oven, to increase the glue strength. The non-aged glue is the glue without a treatment.

3. Test Execution:
   a. Define stressors
      After analyzing the problems the test team defines list of stressors to be applied during the test. The team decides to apply only two classical stressors i.e. temperature and vibration.
   b. Defining test scheme
      In this test, the team defines test scheme based on experience. However, the team exercises the method of determining the temperature limit using the step-stress approach. The highest temperature destruct limit is investigated using the step stress approach with 10° C temperature step and hold for at least 10 minutes in each step. The step stress is starting at one degree below 55° C, this is 10 degree, one step, below the maximum specification limit. The reason of choosing this point is to ensure the fastest arrival to the destruct limit. During performing the step stress, it appears that after 95° C the plastics of the AV2 deform. Therefore, this point is considered as the destruct limit.
      A similar procedure is also applied for the lower temperature destruct limit. The starting point is 15° C, ten degree (one step) above the lower specification limit. However, there is no indication of failure although the temperature already reaches -35° C. Therefore, this point is considered as the lowest temperature limit because below this point is considered already impractical.
   c. Setting up the module on the equipment
      The module is setup inside the test equipment. The module is controlled from outside with a control board that is connected to a personal computer (PC). The PC, outside the equipment, is able to send the necessary commands via the
control board to the AV2. The same PC and control board are also used to read out the beam landing in the AV2.

d. Failure criteria
In this test, the failure criteria are defined by measuring the beam landing. This is the amount of light that the detectors receive. If the value is 0.50 or higher then the product is considered defect.

4. Result
Six AV2 engines with different serial number have been tested. Three of the engines have aged glue and the rest have non-aged glue. The result of the test is shown in Figure AV2-5.

5. Discussion
There are two tests that have been designed for the AV2. The first test is for AV2 that has aged glue and the second test is for AV2 that has non-aged glue. The result of the test, Figure AV2-5, shows that there is a significant different between AV2 with aged and non-aged glue. Therefore this test concludes that the AV2 with aged glue has a lower beam landing than the AV2 with non-aged glue.

Figure AV2-5  AV2 Tests Results
<table>
<thead>
<tr>
<th>No.</th>
<th>Module</th>
<th>Reason for Testing</th>
<th>Prior Failure Mechanism</th>
<th>Type of Failure/Defect</th>
<th>Phase in Four-phase Roller Coaster Curve</th>
<th>Phase in Product Lifecycle (see note)</th>
<th>Failure Found</th>
<th>Replicability</th>
<th>Reproducibility</th>
<th>Replicability</th>
<th>Reproducibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power 4</td>
<td>Electrical</td>
<td>High FCR</td>
<td>Electrical</td>
<td>2</td>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Electrical, Music, Magnetic</td>
</tr>
<tr>
<td>2</td>
<td>5DTC</td>
<td>Both</td>
<td>Reproduce failure</td>
<td>Known</td>
<td>2</td>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Electrical, Environment, User</td>
</tr>
<tr>
<td>3</td>
<td>5DTC</td>
<td>Both</td>
<td>Provoking failure</td>
<td>Unknown</td>
<td>1=2</td>
<td>P</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Electrical, Environment, User</td>
</tr>
<tr>
<td>4</td>
<td>6ch Amp</td>
<td>Electrical</td>
<td>Provoking failure</td>
<td>Unknown</td>
<td>n.a</td>
<td>1=2</td>
<td>Dev</td>
<td>No</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>DVD625</td>
<td>Both</td>
<td>Predicting FCR</td>
<td>Unknown</td>
<td>1=2</td>
<td>P</td>
<td>No</td>
<td>n.a</td>
<td>n.a</td>
<td>n.a</td>
<td>Electrical, Environment, User</td>
</tr>
<tr>
<td>6</td>
<td>AV2</td>
<td>Both</td>
<td>Reproduce failure</td>
<td>Known</td>
<td>2</td>
<td>R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Environment, User</td>
</tr>
</tbody>
</table>

Note: D = Design  
Dev = Development  
PP = Pilot Production  
P = Production  
R = Product return  
FCR = Field Call Rate  
NFF = No Fault Found  
n.a. = Not Available  
Reliable test
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