Analysing Reliability Problems in Concurrent Fast Product Development Processes

ANALYSING RELIABILITY PROBLEMS IN CONCURRENT FAST PRODUCT DEVELOPMENT PROCESSES

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Lu Yuan

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SUMMARY

Modern product development processes (PDPs) are dominated by a strong pressure on "Time-To-Market" (TTM). One of the complex challenges in such a time-driven development process is managing product reliability. This is because reliability information becomes available relatively late in the process while the decisions to determine product reliability have to be taken especially in the early phases of the process. Therefore the first part of this thesis looks into the backgrounds of reliability problems in fast time-driven development processes while the second part of this thesis looks into ways of managing reliability in these processes in an adequate manner.

Based on a literature study in the field of concurrent fast product development processes (CFPDPs)[1] and reliability management, it was concluded that

- Derivative PDPs are more effective in coping with TTM pressure compared with radical PDPs.
- Product reliability does not depend on component reliability alone. It also depends on the business process that develops the product.
- Reliability problems from Phase 1 and Phase 2 of the roller coaster failure rate curve are found to be more critical to PDPs under strong TTM pressure.
- Reliability should be managed proactively in fast PDPs. Concurrent PDPs are most suitable for the development of derivative products under TTM pressure.

Since a CFPDP employs proven technologies to quickly integrate mature building blocks from existing products, there should be, at least according to the theory, very limited unpredicted reliability problems from Phase 1 of the four-phase roller coaster failure rate curve (Phase 1 reliability problems). These particular problems are closely related to products that are outside the specification (failed products) when reaching the customer, or products that are 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. However, the results of the field case studies conducted in a multinational company showed a very strong dominance of these Phase 1 reliability problems in some CFPDPs. Such observations led to the research problem of this thesis: "What causes the unpredicted Phase 1 reliability problems in CFPDPs and how can they be prevented?" Further analysis showed that the uncertain information used in reliability

[1] A CFPDP refers to a derivative product development process (PDP) using the philosophy of concurrent engineering.

prediction, i.e. the required reliability information, was not properly deployed and utilised in the PDP, was responsible for these problems. The case results also demonstrated that one of the most commonly used tools in industry for reliability prediction, Failure Mode and Effect Analysis (FMEA), is not able to predict relevant reliability problems using uncertain information.

The case results urged the development of a new reliability prediction method to include the aspect of uncertainty in reliability prediction. A set of formal requirements was identified based on the experiences from the earlier field studies and literature. Based on these requirements, a method called Reliability and Quality Matrix (RQM) was developed. This method was implemented and evaluated in a CFPDP in the company where the early case studies were conducted and the results are reported in this thesis. The implementation results demonstrated that by using this method it is possible to classify uncertainty when predicting potential reliability problems, to prioritise uncertainty improvement activities, to manage uncertainty in CFPDPs, and to enable product reliability improvement based on certain information in CFPDPs. Consequently, it has the required potential to prevent unpredicted Phase 1 reliability problems in CFPDPs. This method is now a part of the formal CFPDP used in that company.

Although this research was conducted in a single company, this method can be applied to manage uncertainty in similar CDPDPs where similar technologies are used to develop similar products as in this company. The usefulness and validity of this method has been proven in a number of industrial field cases.

SAMENVATTING

Moderne product ontwikkelingsprocessen (Engels: "Product Development Processes" (PDPs)) worden sterk beïnvloed door een grote druk op "Time-To-Market" (TTM). Eén van de grote uitdagingen in een tijdgedreven ontwikkelingsproces is het management van de betrouwbaarheid ("reliability") van het eindproduct. Dit is vooral het geval omdat informatie over reliability relatief laat in het ontwikkelingsproces beschikbaar komt, terwijl de beslissingen die de product reliablity bepalen vooral in de vroege fases van het ontwikkelingsproces worden genomen. Om deze reden is het eerste deel van dit proefschrift geweid aan de achtergrond van reliability problemen in snelle tijdgedreven ontwikkelingsprocessen, terwijl het tweede gedeelte van dit proefschrift met name ingaat op methodes om reliability bij deze processen op een adequate manier te managen.

Gebaseerd op een literatuur studie in het gebied van snelle concurrent ontwikkelingsprocessen (Engels: " Concurrent Fast Product Development Processes" (CFPDPs[2])) en in het gebied van reliability management kunnen de volgende conclusies worden getrokken:

- Evolutionaire PDPs (PDPs van afgeleide producten) zijn effectiever in het omgaan met tijdsdruk (TTM) vergeleken met zogenoemde Revolutionaire PDPs
- Product reliability is niet alleen van de reliability van de componenten. Product reliability is ook afhankelijk van de bedrijfsprocessen die het product realiseren.
- Reliability problemen die optreden in fase 1 en 2 van de "roller coaster" kromme zijn meer relevant in ontwikkelingsprocessen onder sterke tijdsdruk (TTM).
- Concurrent ontwikkelingsprocessen zijn het meest geschikt voor de ontwikkeling van afgeleide producten onder tijdsdruk (TTM).
- Een dergelijk ontwikkelproces eist een hoge mate van voorspelbaarheid (en daarmee vroegtijdige beheersbaarheid) van reliability problemen

Omdat hierdoor in snelle concurrent ontwikkelingsprocessen gebruik gemaakt moet worden van bekende technologie, zouden er theoretisch gezien geen onvoorspelde reliability problemen in fase 1 moeten optreden. Deze fase 1 problemen zijn namelijk gerelateerd aan producten buiten specificatie (gefaalde producten), of aan producten

[2] Een CFPDP heeft betrekking op een ontwikkelingsproces van een afgeleid product waarbij de filosofie van "concurrent engineering" wordt gebruikt

binnen specificaties, maar onacceptabel voor de klant vanwege incomplete specificaties of een andere perceptie van het product door de klant. De resultaten van de veldstudies beschreven in dit proefschrift laten echter juist een grote bijdrage van deze fase 1 reliability problemen zien. Deze observaties hebben geleid tot de onderzoeksvraag van dit proefschrift: "Wat veroorzaakt de niet voorspelde fase 1 problemen in snelle concurrent ontwikkelingsprocessen en hoe kunnen deze voorkomen worden?". Verdere analyse laat zien dat onzekere informatie een belangrijke oorzaak was van dergelijke problemen. De resultaten van de veldstudies lieten ook zien dat een van de in de industrie meest gebruikte gereedschappen voor reliability voorspelling, de Failure Mode en Effect Analyse (FMEA) niet bruikbaar is om reliability problemen te voorspellen in het geval van onzekere informatie.

De veldstudies lieten de noodzaak zien van de ontwikkeling van een nieuwe reliability voorspellingsmethode die ook het aspect onzekerheid kan meenemen. Op basis van literatuur en veld experimenten is een set van formele eisen voor een dergelijke methode opgesteld. Vanuit deze eisen is een nieuwe methode ontwikkeld, genaamd Reliability and Quality Matrix (RQM). RQM werd geïmplementeerd en getest in een CFPDP in het bedrijf waar de eerste praktijkstudies werden gedaan. De resultaten van deze implementatie lieten zien dat het met behulp van RQM mogelijk is om bij potentiële reliability problemen onzekerheid te kunnen classificeren, verbeteracties te kunnen prioriteren, onzekerheid in snelle concurrent ontwikkelprocessen te kunnen beheersen en gebaseerd op zekere informatie het product reliability in deze processen te kunnen optimaliseren. Daarom heeft RQM het potentieel om onverwachte fase 1 reliability problemen in snelle concurrent ontwikkelingsprocessen te voorkomen. Deze methode is nu deel van het formele concurrent ontwikkelingsproces in het bedrijf waar de eerste praktijkstudies werden gedaan.

Hoewel het onderzoek is uitgevoerd in een enkel bedrijf kan de ontwikkelde methode ook toegepast worden in vergelijkbare bedrijven waar met behulp van vergelijkbare bedrijfsprocessen vergelijkbare producten ontwikkeld worden. De bruikbaarheid en validiteit van deze methode zijn inmiddels gedemonstreerd in een aantal industriële veldtesten.

TABLE OF CONTENTS

NOMENCLATURE

AFM	Approval Functional Model
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CD	Compact Disc
CFPDP	concurrent fast PDP
CMD	Commitment Date
CR	Commercial Release
CS	Concept Start
DFM	Design for Manufacturing
DOE	Design of experiment
DR	Design Release
FMEA	Failure mode and effect analysis
IR	Industrial Release
MPR	Mass Production Release
NP	Noise Problem
OEM	Original Equipment Manufacturer
PDP	product development process
PMG	Product Maturity Grid
PMP	Proactively Managed Problem
PPP	Poorly Predicted Problem
PRS	Product Range Start
QFD	Quality Functional Deployment
RMP	Reactively Managed Problem
RQM	Reliability Quality Matrix
SPC	Statistical Process Control
SR	Specification Release
TTM	time-to-market

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION

The outline of this chapter is given as follows. In Section 1.2, the research framework is explained. In Section 1.3 the problem statement, research questions and research objective are formulated, followed in Section 1.4 by the research methodology deployed in this research project. A number of important concepts are listed in Section 1.5. The outline of this thesis is given in the end.

1.1. Research Framework

Product development is operating in a turbulent environment now. Fast technology innovation (Goldhar et al., 1991; Wheelwright and Clark, 1992; Nijssen et al., 1993; Birnbaum, 1998; Minderhoud, 1999; Brombacher and de Graef, 2001), increasing globalisation and segmentation (Classen and Lopez, 1998; Murthy et al., 1994; Brombacher and de Graef, 2001) in product development activities, increasing complexity in customer requirements and perceptions over product performance (Goldhar et al., 1991; Wheelwright and Clark, 1992; Brombacher and de Graef, 2001), and increasing pressure on time-to-market (TTM) (Stalk and Hout, 1990; Goldhar et al., 1991; Wheelwright and Clark, 1992; Minderhoud, 1999) have created a highly competitive market for many industries. The high-volume consumer electronics industry is a typical example. Companies that are operating in this competitive market have to plan their product development activities carefully so that they can provide products that achieve customer satisfaction as well as gain sufficient profit and maintain their market position. This thesis is interested in research on product development under TTM pressure.

Recently, especially in the last decade, TTM has become a watchword in many industries. To keep up with competition and continue to grow, it has become necessary for firms to introduce more products to the market faster. Firms that succeed in developing and marketing new products faster than competitors can obtain many advantages, including gaining a large market share and higher profit by commanding a premium price (Foo et al., 1995; Brooks and Schofield, 1995). Product development processes (PDPs) under such time pressure are required to deliver good products much faster than before.

It has been recognised for a long time that derivative PDPs are more capable of dealing with strong TTM pressure compared with radical PDPs (Smith and Reinsertsen, 1991; Wheelwright and Clark, 1992; Minderhoud, 1999). This observation has led to an incremental approach to product innovation in order to reduce TTM because this incremental development strategy can reduce risk, generate positive cash flows more rapidly, and enable access to early market feedback for midcourse corrections. An interesting example was published by the Wall Street Journal in 1990 about GE's failed introduction of a new refrigerator with a totally new rotary compressor. Over 1 million refrigerators had to be recalled and fixed. This example was used quite often to demonstrate that it is very risky to launch a highly innovative product too early. One typical example of successful derivative products is the Intel® Pentium III processor (Intel, 2002). This thesis therefore names derivative PDPs under TTM pressure as fast PDPs.

Most literature related to fast PDPs mainly stresses how successful they can be when dealing with TTM pressure and how many advantages they can bring to companies. Little attention was given about how to improve such PDPs when they are not as successful as expected. This research project is especially interested in improving product reliability in fast PDPs.

One of the ways to measure reliability of products is by using the failure rate. A bathtub shaped failure rate curve is sometimes used to model the different phases of failure rate (Lewis, 1996) by classifying product failures into three groups: infant mortality, random failures and wearout. In the past and even now in some industries, a constant failure rate model is often used to predict product reliability, which is related to the "random failure" phase of the bathtub failure rate curve (Lewis, 1996). Recently, reliability problems from early phase of the bathtub curve have been found to be more critical especially under the increasing TTM pressure (Lu et al., 2000). By investigating the early phase of the bathtub curve in detail, a four-phase roller coaster failure rate curve, was introduced (Wong, 1988; Brombacher, 1992). This research project analyses reliability problems from Phase 1 of the four-phase roller coaster failure rate curve (Phase 1 reliability problems) in fast PDPs. Phase 1 reliability problems are those due to products out of the specification of the manufacturer, or incomplete specification of the manufacturer or mismatch between the specification of the manufacturer and its customer or consumer.

In order to deal with time pressure, a PDP requires a very high predictability[3] (Brombacher and de Graef, 2001). It implies that potential reliability problems in such a PDP should be managed proactively. Brombacher et al. (2001) identified four PDP structures based on how reliability is managed in the PDPs: functional PDPs vs. reactive reliability management, sequential PDPs vs. interactive reliability management, concurrent PDPs vs. proactive reliability management, and dynamic PDPs vs. iterative reliability management. Among these, concurrent PDPs are found to be most suitable for the development of derivative products with strong time pressure (Eisenhardt and Tabrizi, 1995; Brombacher et al., 2001). These PDPs are named as "concurrent fast PDPs (CFPDPs)" in this thesis. This research project focuses on improving Phase 1 reliability problems in CFPDPs.

In CFPDPs, product reliability should be managed proactively. Berden et. al (2000) highlighted the fact that anticipation is only possible if enough information about the PDP is available. Since a CFPDP employs proven technologies to quickly integrate mature building blocks from existing products, it is theoretically possible to fully predict and prevent Phase 1 reliability problems. Expecting such high degree of predictability leads to the formulation of the proposition of this thesis. A more detailed analysis of the research framework and corresponding literature can be found in chapter 2.

Proposition: Since a CFPDP employs proven technologies to quickly integrate mature building blocks from existing products, there should be very limited unpredicted Phase 1 reliability problems.

1.2. Problem Statement, Research Questions and Research Objective

As discussed earlier, a CFPDP requires proactive predictability of potential reliability problems and it is theoretically possible to fully predict and prevent Phase 1 reliability problems in this PDP. Such a PDP exists not only in a business-to-business company but also in a business-to-end user company. There are two sources of information related to actual product reliability problems for a business-to-business manufacturer: from customers, and from end-users, while there is one source of information for a business-to-end user manufacturer: from end-users. On the one hand, the product reliability information from the end users is more logistics oriented and is insufficient to be used to improve product reliability in a PDP (Petkova et al., 2000, Molenaar et al., 2002). On the other hand, the product reliability information from the customers relates more closely to actual product early reliability behaviour and can be used to identify the Phase 1 reliability problems. Therefore, in order to verify the proposition, observations

[3] The likelihood that potential reliability problems become predicted.

have been made in business-to-business CFPDPs in one multinational company. According to the observations, this proposition does not hold for these CFPDPs in this company. Therefore, the research engaged in this thesis aims to identify the following research problem:

What causes the unpredicted Phase 1 reliability problems in CFPDPs and how can we prevent them?

Consequently, two research questions are derived and will be answered in this thesis. They are

Research question 1: What causes unpredicted Phase 1 reliability problems in CFPDPs?

Research question 2: How can these problems be prevented?

Therefore, the main research objective of this thesis is:

Developing a reliability prediction method to predict previously unpredicted Phase 1 reliability problems in CFPDPs

1.3. Research Methodology

It is not necessary for all researchers to become experts in methodology, but they should be aware that the way that a methodology is chosen affects the validity of any conclusion that they draw from their research (Ramsey, 1998). In this section, the research methodology employed in this research is discussed in connection with the methodology literature.

1.3.1. Research Classification

There are many different classifications of research methodology in the literature. Two important classifications relevant to this research are briefly discussed below.

Based on the type of knowledge that is generated, design knowledge or conventional theories, a research project can be classified as design research or theoretical research (Simon, 1996; Suh, 1990; Aken, 1994; Verschuren and Doorewaard, 1999). Design knowledge is different from conventional theories. The former describes how things ought to be while the latter argues how things are.

Another classification is given by Verschuren and Doorewaard (1999). They identified two different types of research projects based on their research objectives. One is more theoretically-oriented by focusing on solving a problem encountered in the theory building process. The other is more applied-oriented by intervening in order to change an existing practical situation.

The research described in this thesis can be classified as **design**-oriented **applied** research since this research project aims at designing a possible solution to predict (unpredicted) reliability problems in CFPDPs and will also improve product reliability. The research results will be presented in the form of design knowledge. According to (Aken, 1999), design knowledge consists of design models and heuristic statements. Design models are defined as operational guidelines that are applicable for a specific application domain while heuristic statements define guidelines and principles by which to operate (Aken, 1999). Together they describe what should be done in order to attain a desired situation.

1.3.2. Research Method

It has been discussed in literature that case studies can be applied in the area of theory testing (Yin, 1994; Verschuren and Doorewaard, 1999), theory development (Eisenhardt, 1989) as well as problem solving (Den Hartog and van Sluijs, 1995). In general, case studies are often preferred when researchers have little control over the event and when the focus is on a contemporary phenomenon in some real-life context (Yin, 1994). In addition, a case study offers a possibility to gain an overall picture of a research (Verschuren and Doorewaard, 1999). This research project intends to prevent unpredicted reliability problems in CFPDPs. Initially little knowledge was available of these reliability problems and to get an overall picture of these reliability problems, a case study approach has been chosen as the main research method in this research project. Case studies were conducted to identify the research problem, to analyse the research problem, and to implement and to test the developed method. Detailed case methods will be addressed accordingly in the following thesis.

1.3.3. Research Program

This research project is a design-oriented applied research. Like all other design research projects, this research also went through a regulative cycle: problem identification, diagnosis, design, intervention, and evaluation (Aken, 1999). Four main stages corresponding to the five steps can be distinguished in this research.

- ♦ Problem identification stage. This stage was further broken down into three sub-stages.

- Formulating proposition by studying relevant literature
- Studying the proposition in a real life product development company
- Identifying research problem, research questions and research objective

♦ Diagnosis stage. In the second stage, the root causes of unpredicted Phase 1 reliability problems was further analysed based on empirical studies in the same company.
♦ Design stage. In the third stage, a number of formal requirements were derived based on literature study and empirical studies and they were used to develop a reliability prediction method.
♦ Implementation/evaluation stage: This method was further implemented and evaluated in a real life CFPDP.

Table 1.1 Main steps of the research program

Research program	Research contents
Problem Identification	Formulating proposition based on analysis of relevant literature; Stating research problem, identifying research questions and defining research objective
Diagnosis	Analysing the root causes of unpredicted reliability problems
Design	Identify the formal requirements for managing unpredicted reliability problems; Translating the formal requirements into a reliability management method
Implementation/evaluation	Implementing this method in a real life CFPDP and evaluating the results

1.4. Important Definitions

In this section, a number of important definitions used in this thesis are listed. These definitions may be quoted or refined again in the following thesis when necessary. Some of these definitions may have different meanings if they are viewed outside this thesis; however, they are adjusted here to fit most within the scope of this thesis.

Table 1.2 Important definitions

Terminology	Definitions
Quality	The total features and characteristics of a product or service that bear on its ability to satisfy given needs (Lewis, 1996)
Reliability	The probability that a system will perform its intended function

	for a specific period of time under a given set of conditions (Lewis, 1996)[4]
PDP	A process that systematically transforms new product ideas into a set of products that could be used by end users or to manufacture other products
TTM	The length of time it takes to develop a new product from an early initial idea for a new product to initial market sales (PDMA, 2001)
Platform products	The design and components that are shared by a set of products in a product family. From this platform, numerous derivative products can be designed. (PDMA, 2001)
Derivative products	Products that are developed based on existing products with small incremental changes
Derivative PDP	A PDP that develops derivative products
Failure	A product failure occurs when the product does not perform according to the agreed specification at the customers
Known technologies	Technologies are considered to be known to the organization if they have been applied under comparable circumstances before in the organisation
Unknown technologies	Technologies are considered to be unknown to the organization if they have not been used before
Failure rate	Failure rate, $\lambda(t)$, can be defined in terms of the reliability of a product at time *t*. Note that T is time to failure for non-repairable products or time to first failure for repairable products[5]. In fact, $\lambda(t)\Delta t$ is the probability that a product will fail at some time $T < t + \Delta t$ given that it has not yet failed at $T = t$. Thus, it can be expressed using a conditional probability. $$\lambda(t)\Delta t = P[T < t + \Delta t \mid T > t] = \frac{P[T > t] \cap P[T < t + \Delta t]}{P[T > t]} = \frac{P[t < T < t + \Delta t]}{P[T > t]}$$ Then failure rate can be expressed as

[4] Reliability can be considered as time dependent quality.

[5] In this thesis, reliability problems of repairable products, which causes first failure of these products in time, are studied.

	$$\lambda(t \to t+\Delta t) = \frac{1}{\Delta t} * \frac{F(t \to t+\Delta t)}{N_{operational}(t)}$$ in which F refers to the number of failures in the given time interval, N refers to the number of operating products on the market in the given time interval, and *t* refers to the time since sales or commissioning of the product (Lewis, 1996).
MTBF	The expected value of the time between failures (Lewis, 1996)
Business-to-business	Non-consumer purchasers such as manufacturers, resellers (distributors, wholesalers, jobbers and retailers, for example) institutional, professional and governmental organizations, frequently referred to as ‘industrial’ businesses in the past (PDMA, 2001)
Customer	A company who purchases or uses a business-to-business company's products or services to produce its own products or services for its customer
End-user	A person purchases and uses products or services of any company and does not produce his own products or services
Quality Functional Deployment (QFD)	A structured method employing matrix analysis for linking what the market requires to how it will be accomplished in the development effort. (PDMA, 2001)
Failure Modes and Effects Analysis (FMEA)	A technique for enumerating the possible failure modes by which components may fail and for tracing through the characteristics and consequences of each mode of failure on the system as a whole. (Lewis, 1996)
Information	Knowledge and insight, often gained by examining data (PDMA, 2001)
Quality of information	Correctness, Completeness, Up-to-date, Verifiable, Accuracy, (selection, detail level) of information (Bemelmans, 1991)
Information flows	Information exchanges taking place within process communication networks that involves systematic sending and receiving of specific messages, and leading to the development of stable patterns of communication in any business process (Adapted from (Forza and Salvador, 2001))

1.5. Outline of the Thesis

The remainder of the thesis is organised as follows. In Chapter 2, the results of a literature study are presented to describe the research framework of this thesis: Phase 1 unpredicted reliability problems in CFPDPs. A proposition is formulated thus: since a

CFPDP employs proven technologies to quickly integrate mature building blocks from existing products, there should be very limited unpredicted Phase 1 reliability problems, from which the research problem, the research questions and the research objective are identified. Chapter 3 describes an empirical study by which the proposition is found to be not true in a multinational company. In Chapter 4 the results of empirical studies are discussed to identify the root causes of unpredicted Phase 1 reliability problems. In Chapter 5, the requirements for predicting unpredicted Phase 1 reliability problems in CFPDPs are derived and a reliability prediction method is proposed, followed in Chapter 6 by the implementation and evaluation of this method in a real life CFPDP in the same company. Finally in Chapter 7, conclusions are drawn and suggestions for future research are given.

CHAPTER 2 RELIABILITY PROBLEMS IN CONCURRENT FAST PRODUCT DEVELOPMENT PROCESSES

In this chapter, the research focus of this research project is built up by examining the relevant literature and by formulating the initial proposition from which a suitable research problem will be identified. In Section 2.1, general trends in product development are first discussed. In Section 2.2, it is discussed that derivative PDPs are more effective in coping with time constraints. In Section 2.3, the traditional constant failure rate model is reviewed and the four-phase roller coaster curve is found to be more appropriate for modelling product reliability when time pressure is high. In Section 2.4, four different reliability management methods are reviewed in connection with fast PDPs under time constraint. Section 2.5 concludes with the initial proposition of this thesis.

2.1. Trends in Product Development

Brombacher and de Graef (2001) highlighted the fact that product reliability has to be modelled as a function of products, the way that these products are designed and manufactured, and the way that customers and end-users use these products. Therefore, a thorough understanding of the current trends in product development is necessary for analysing reliability problems in PDPs. In this section, recent trends in product development in consumer electronics industry are discussed.

Manufacturing companies have long recognized that product development activities add value to the business and a PDP is their core business process (Berden et al., 2000). Wheelwright and Clark (1992) commented that firms that can develop products, which can satisfy the needs and expectations of customers, and can market them much faster and more efficiently, create significant competitive advantages. Four major recent trends in product development are observed from the literature.

2.1.1. Increasing Product Complexity

Product development at its core involves selecting and integrating technologies and matching them to their application context — the product's customer and manufacturing/service delivery environment. Fast technology innovation naturally contributes to the increasing complexity in products. Technology innovation is now taking place at a dramatic speed and width (Birnbaum, 1998; Nijssen et al., 1993; Wheelwright and Clark, 1992). Wheelwright and Clark (1992) mentioned that the growing breadth and depth of technological and scientific knowledge has created new options for meeting the needs of customers. By looking at the evolution of personal computers during the last 5 years, for example, it is not difficult to experience the increasing rate of strong technology push. Not only is the complexity of the technical contents of products increasing, but the diversity and the variety of products as well (Minderhoud, 1999; Goldhar et al., 1991). The availability of large varieties of personal communication equipment due to the introduction of information technology into the consumer electronics industry is a typical example. The challenge to companies is then how to handle the increasing product complexity in their PDPs so as to deliver a product that satisfies customer requirements.

2.1.2. Increasing Time-To-Market (TTM) Pressure

There is a broad agreement that improved mass communications and rapidly changing technologies are the two important causes of achieving shorter TTM (Rosenau, 1998). This is because, firstly, information about the latest new product reaches the intended user or the purchaser faster, which promotes an earlier switch away from the existing product; secondly, rapidly changing technologies also make it easier to develop an innovative new product that offers advantages to users. By reducing TTM, companies bring more products faster to the market and the existing products also get obsolete faster than before. It results in the observation that product commercial life cycles are getting shorter (Minderhoud, 1999; Goldhar et al., 1991). The important life cycle of a product that matters to manufacturers is therefore not its physical life cycle but its commercial life cycle.

Time-based competition has been long recognized as a fine way to achieve competitive advantages in the dynamic environment today. Although the early discussion on these issues (Stalk and Hout, 1990) dealt with the process of taking orders, manufacturing individual units, and delivering products, reducing TTM has also become a critical objective for most companies in the 90s' (Wheelwright and Clark, 1992). There are many advantages for companies to reduce TTM. Being first in the market gives companies the opportunity to set the standard and to secure a larger market share with increased product revenues from the extended sales life; early entry into the market also gives companies an opportunity to command a price premium and hence higher profit margin; reducing the product development time allows companies to start later, with the opportunity to incorporate the latest features and technology (Foo et al., 1995; Brooks and Schofield, 1995). Many technology-driven firms, therefore, have started competing on how fast they can bring a product to the market. Many techniques have been suggested and successfully used to shorten the PDP while maintaining product quality. These include

- Parallel or concurrent processing of the PDP steps (Takeuchi and Nonaka, 1986; Karagozoglu and Brown, 1993; Murmann, 1994)
- Improving the R&D–marketing–manufacturing interface by establishing cross-functional teams (Griffin, 1992; Towner, 1994; Towner, 1994)
- Putting more human resources and financial investments at the front end of the project (Smith, 1988)
- Increasing rewards for R&D performance (Gold, 1987)
- Changing to a more participative leadership style (McDonough and Barczak, 1992)
- Reducing product complexity (Smith and Reinertsen, 1991; Minderhoud, 1999; Wheelwright and Clark, 1992; Murmann, 1994)

Much has been reported about reducing TTM. Page (1993) reported in a study sponsored by the organisation of Product Development and Management Administration (PDMA) that over 40% of responding firms have reduced their cycle time since 1987. Trygg (1993) did a comparable study in Sweden and reported that over 50% of firms had reduced their TTM. Various other studies (Kleinfield, 1990; Hof, 1992; Crawford, 1992; Millson et al., 1992; Rosenthal, 1992; Griffin, 1993; Towner, 1994; Maynard, 1997) have also reported similar successful stories.

Since so many industries have successfully reduced their TTM in the 90's, the focus of product development is gradually moving from reducing TTM to maintaining and improving PDPs that operate in the reduced time frame (Oorschot, 2001). Time is then no longer a target but rather a constraint to PDPs and industries are expected to deliver their products developed under the reduced TTM with better reliability. This research project also focuses on a time-driven PDP. Time-driven PDPs refer to time-constrained PDPs.

2.1.3. Globalisation and Segmentation

Increased international competition in 1990s requires many product development activities to be managed and governed globally, which is very different from purely domestic endeavours. Many companies from America, Europe and Asia, like Motorola, Philips and Sony, have not only opened manufacturing sites in the Far Eastern and Asia

Pacific countries but also delivered their products from these sites to countries in Europe and America, in response to the globalisation and segmentation trend of the business and economic environment (Murthy et al., 1994). Classen and Lopez (1998) described the globalisation trend in the computer industry. Since the computer industry is a very competitive market, companies are competing in all aspects especially on setting aggressive product price in order to gain profit margins via high volume. A common practice for computer manufacturers, therefore, is to use geographically dispersed factories to obtain market positions around the world and to secure reasonable levels of profit. Brombacher and de Graef (2001) provided an example of a recent development process of CD players with all the parties involved in different geographical locations. Under this circumstance, companies have to take a global management approach in their PDPs to maintain and increase their market shares as well as to achieve customer satisfaction.

2.1.4. Increasing Customer Requirements

In the definition of reliability that was discussed earlier, a product is said to have failed if it does not fulfil its intended purpose. The exact meaning of "intended purpose" has changed dramatically. In the past, a product failure meant that it did not work according to its specification. More recently, a product is considered to have failed if customers are simply dissatisfied with its performance. More and more scholars observed the trend of increasing customer requirements in the industry. Goldhar et al. (1991) described how customers are becoming increasingly more sophisticated and are demanding customized products more closely targeted to their needs. Wheelwright and Clark (1992) also observed that customers have grown more sophisticated and demanding because they are more sensitive to nuances and differences in a product, and are attracted to products that provide solutions to their particular problems and needs. Brombacher and de Graef (2001) highlighted the fact that even when a product works according to its specification but a certain customer or group of customers is very unhappy with the functionality, the product will still be perceived as unsatisfactory as to its reliability. They also gave an example of the change in warranty structure in consumer products over the last ten years. According to the example, in the past, warranties covered only the replacement or repair of the defective products returned within 6 months to 1 year after sales; currently, warranties tend to cover any customer complaints within 3 years after sales.

2.2. Fast Product Development Processes

2.2.1. What is a Product Development Process?

There are several definitions of a PDP in the literature (Andreasen and Hein, 1987; Clausing, 1994; Mcgrath, 1996; Hanssen, 2000; PDMA, 2001). Hanssen (2000) uses a general PDP that starts with a perception of market needs and ends with the market introduction of a new or improved product without taking into account the many differences between each product development project. Product Development and Management Association (PDMA) defined a PDP as a disciplined and defined set of tasks and steps, which describe the normal means by which a company repetitively converts embryonic ideas into saleable products or services (PDMA, 2001). Clausing (1994) gave a more specified definition of a PDP: a process to develop products through the phases of concept, design and production. Other definitions sometimes gave more details of a PDP by breaking the three phases defined by Clausing further into more detailed development activities.

Taking into consideration the definitions given by (PDMA, 2001) and Clausing (1994), a general PDP in this thesis is considered as a process that systematically transforms product ideas into new products that could be used by customers. Three basic phases are included.

- Concept development starts with a product idea or a request from a customer for a certain product. It is followed by a feasibility study to test the practicality of the various product concepts and refine the requirements. This concludes with a product development assignment where a plan with cost and resource consideration is defined to support the development of the chosen product concept.
- Product design consists of a diverse range of tasks. It includes hardware design, software writing and product testing to ensure compliance with customer requirements, etc.
- Production then realizes the product design into a physical product in a manufacturing plant. It encompasses production equipment preparation, production line set up, training for new operators and actual production and delivery to the customer.

2.2.2. Radical and Derivative PDPs

As discussed earlier, increasing TTM pressure requires companies to develop many different products much faster than they used to. The purpose of producing a large range of products is to meet different customers' requirements in different markets based on existing and future technology capabilities (Wheelwright and Clark, 1992).

Based on the degree of technical changes in products as well as their applications, two major types of PDPs can be distinguished (Andreasen and Hein, 1987, Wheelwright and Clark, 1992).

- Radical PDPs: These PDPs develop radical products. Radical products are new products, which generally contain new technologies and significantly change behaviours and consumption patterns in the marketplace. The first DVD player in the market is an example of a product developed in a typical radical PDP.
- Derivative PDPs: These PDPs develop derivative products. They use proven technologies to create products based on mature building blocks from existing products. They modify, refine, or improve some product features without affecting the basic product architecture or platform. Such processes usually require substantially fewer resources than processes that develop totally new products. Intel developed Pentium (III) processors in typical derivative PDPs.

Of these two types of PDPs, radical PDPs have the potential to capture a larger market share from competing products. However, they may take too long to complete their task. Consequently, a company may miss the market introduction windows if it depends on radical PDPs alone. Hayes et al. (1988) reported an example of Apple's Lisa-Macintosh development effort in the early 80s. The development project was extremely ambitious and aimed to make major improvements in both product performance (hardware and software) and manufacturing process development. The several quarters of delay in the product's introduction drove Apple's earnings down dramatically and caused the stock of the company to fall to less than half of its early 1983 value by the time that the product was finally introduced.

Researchers (Minderhoud, 1999; Smith and Reinertsen, 1991; Wheelwright and Clark, 1992) have long recognised that taking an incremental approach in a PDP has good potential for dealing with TTM pressure because the amount of effort and learning that must be done per product type is reduced and so is the amount of time needed to invest in new technologies prior to the product launch. An incremental strategy also reduces risk, generates positive cash flows more rapidly, and enables access to early market feedback for midcourse corrections (Wheelwright and Clark, 1992). Such perspectives have led many established firms to adopt this philosophy in dealing with TTM pressure. Besides the ambitious introduction of radical products with advanced technologies, derivative products are also planned. Reducing product complexity has been chosen as one of the strategies to achieve short TTM (Smith and Reinertsen, 1991; Minderhoud, 1999; Wheelwright and Clark, 1992; Murmann, 1994). Thus derivative PDPs are also included among "fast PDPs" in this thesis. Besides benefiting companies in being fast to the market, fast PDPs also have other advantages that are of interest to companies. These PDPs enable early market feedback for midcourse corrections. Extensive reuse and leverage in such PDPs enable companies to rapidly evolve a product through successive generations by concentrating on improving only a few components or subsystems at a time. One typical example of these derivative products is the Intel® Pentium III 256 KB processor (Intel, 2002). From January 1999 to July 2000, Intel introduced Pentium III 256 KB processors at 7 different core speeds ranging from 450 MHz to 1.33 GHz. By doing so, Intel has been able to provide users with a wide range of flexibility.

As discussed, most literature relating to fast PDPs mainly highlights how successful the PDPs can be when dealing with TTM pressure and how many advantages they can bring to companies. Little attention was given about how to improve PDPs when they are not as successful as expected. This research project is, in particular, interested in improving product reliability in fast PDPs.

2.3. Product Reliability under TTM Pressure

As defined earlier, reliability is considered as a function of time. This time-dependence leads to the definition of failure rate (Lewis, 1996). A bathtub failure rate curve is sometimes used to model the different phases of failure rate (Lewis, 1996). It reveals the natures of reliability problems: whether they are early failures (infant mortality), or failures occurring randomly in time, or failures due to aging effects. Under strong time pressure, it is not possible to prevent all of these failures in fast PDPs. Then the question is what should be prevented. In the past and even now in some industries, a constant failure rate model is often used to predict reliability, which is related to the "random failure" phase of the bathtub failure rate curve (Lewis, 1996). For a very long time, this constant failure rate model has been proven to be invalid (Codier, 1969). Especially recently reliability problems from early phase of the bathtub curve have been found to be more critical, especially under the increasing TTM pressure (Lu et al., 2000). By investigating the early phase of the bathtub curve in detail, a four-phase roller coaster failure rate curve, was introduced (Wong, 1988; Brombacher, 1992). In this section, a review of the traditional constant failure rate model is given first. Next based on evidence from literature it is argued that the constant failure rate model is no longer valid for products that are developed under strong TTM pressure. Then the four-phase roller coaster failure rate model is discussed. This section is concluded when stating the focus of this thesis: analysing reliability problems in Phase 1 of the four-phase roller-coaster failure rate curve in fast PDPs.

2.3.1. Constant Failure Rate Model

Many researchers (Blanks, 1998; Denson, 1998; Knowles, 1999; Brombacher, 2000) have pointed out that the traditional reliability prediction methods assume that the failure rate of a product is primarily determined by the components comprising the product. Structures were set up to collect field performance data for components and the resultant data are translated into standard reliability prediction handbooks (Knowles, 1999). In order to understand the background of the component-based reliability prediction methods, the first practical product reliability model for non-repairable products or repairable products before time to first failure, a (three phase) bathtub failure rate curve (Lewis, 1996), is discussed. This model describes the failure rate of a product as a function of three different aspects:

♦ Phase 1: Early failures; failures due to flaws in production or in the material used in the product. For eliminating such failures, Lewis suggested the use of design and production quality control measures to reduce the variability and hence the susceptibility to the infant mortality failures. If such measures are not sufficient, he also recommended implementing burn-in or wear-in of the product for a period of time so that this phase can be screened out.

♦ Phase 2: Random failures/random failures; failures induced by random events. Improving designs can reduce this type of failures. Lewis (1996) suggested that by making products more robust to the environment, i.e. improving the product capabilities relatively higher to its loads, the chance of product failure in phase 2 is getting lower.

♦ Phase 3: Wear-out failures, failures due to degradation mechanisms in a product. In this phase, the aging failure becomes dominant. Lewis (1996) suggested that there are a few approaches that can be deployed to prolong the product lifetime, including design with more durable components and materials and control of deleterious environmental stresses.

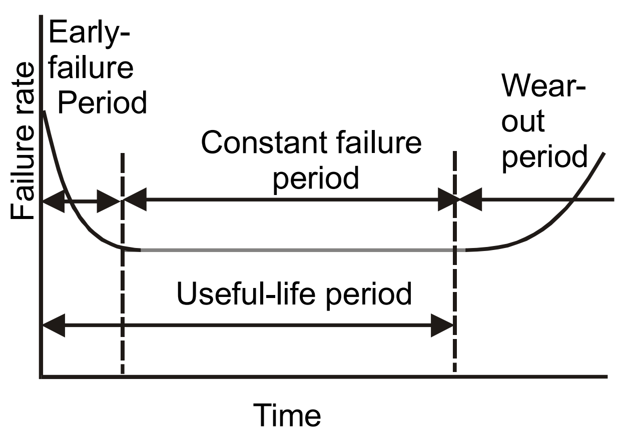

Figure 2.1 Bathtub failure rate curve

Jensen (1995) used a stress-strength relationship to explain this bathtub failure rate curve. The first part of the bathtub curve, known as the early failure or infant mortality, exhibits a decreasing failure rate. According to (Jensen, 1995), the early failures may be due to

- Poor materials/process, including poor manufacturing techniques, poor process control (human factor and quality control) and poor materials.
- Poor design, including insufficient tolerance design, etc.

The fairly flat portion of the failure rate curve is also called the useful life, random failure or intrinsic failure period. Jensen (1995) suggested that random failures might be caused by higher than expected external random stresses. The last part of the curve is known as the wear-out failure period. Wear-out failures may be caused by inherent degradation and long-term drift (Jensen, 1995).

In the early fifties, intensive testing programs were designed to eliminate the first phase while replacement with new products takes place to remove the third phase. The only phase that needs to be managed was the constant failure rate. Phase 2, the constant failure rate, then becomes the only relevant part of the curve to the product development people. That is why many industries use the constant failure rate approximation, i.e. the exponential distribution, to describe the reliability behaviour of their components even though their products may exhibit moderate early failures as well as/or aging effects. Under the assumption that only components determine product reliability, the component failures are independent of one another, and the only relevant reliability behaviour of these components is the constant failure rate period, the failure rate of a series system can, therefore, be simply modelled as the summing up of the constant failure rate of each component, which is also constant (Lewis, 1996). Based on this model, many industry standards have been developed to predict the system failure rate using this simplified model (MIL, 1986; BT, 1987). This kind of prediction models became very popular in industry because they are very simple and easy to implement.

The constant failure rate assumption greatly simplifies the mathematics and analyses needed for estimating the product reliability. However, when this simplification is applied to products where early failures or aging failures are not negligible, then the constant failure rate assumption cannot give accurate results on product reliability performance. Many researchers have shown that simply adding up constant failure rates can produce results that are highly inaccurate and far from realistic (Pecht, 1994; Wood and Elerath, 1994; Mortin et al., 1995; Bothwell et al., 1996; Brombacher, 1992). However, it is commonly used even today but most of the time, users neglect the basic assumptions of this method:

- Components only operate during its the constant failure rate period
- System reliability is assumed to be a function of the component reliability only

♦ Rigorous testing programs have to be in place to remove the first phase of the failure rate curve (Denson, 1998; Bradley, 1999; Brombacher, 2000)

Recently, field product reliability behaviours suggested that product reliability might not depend on component reliability only. An important number of product failures in the field also stem from non-component causes such as defects in design and manufacturing. However, these factors have not been stressed in the component-based failure rate model. Brombacher (1996) found out in one of his field studies that only 21% product reliability problems were related to component reliability (Figure 2.2).

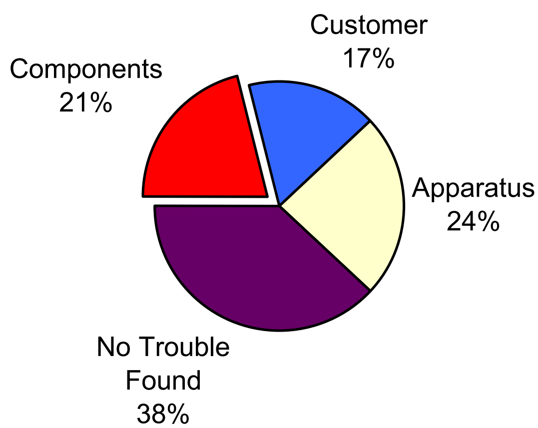

Figure 2.2 Observed product reliability problems (Brombacher, 1996)

Moreover, Blanks (1998) suggested that product design/development procedures and disciplines should also be taken into consideration. Denson (1998) reported 8 different sources of reliability problems of electronic systems (Table 2.1) based on the data collected by the Reliability Analysis Centre (RAC).

Table 2.1 Failure sources of electronics systems (Denson, 1998)

Failure sources	Failure percentage
Parts	22%
Manufacturing	15%
Induced	12%
Design	9%

Wearout	9%
Software	9%
No defect	20%
System management	4%

Figure 2.3 shows similar results by Bradley (1999). All of these results demonstrate that product reliability nowadays does not depend in a major way on component reliability, but that it also depends on the business process that generates the product.

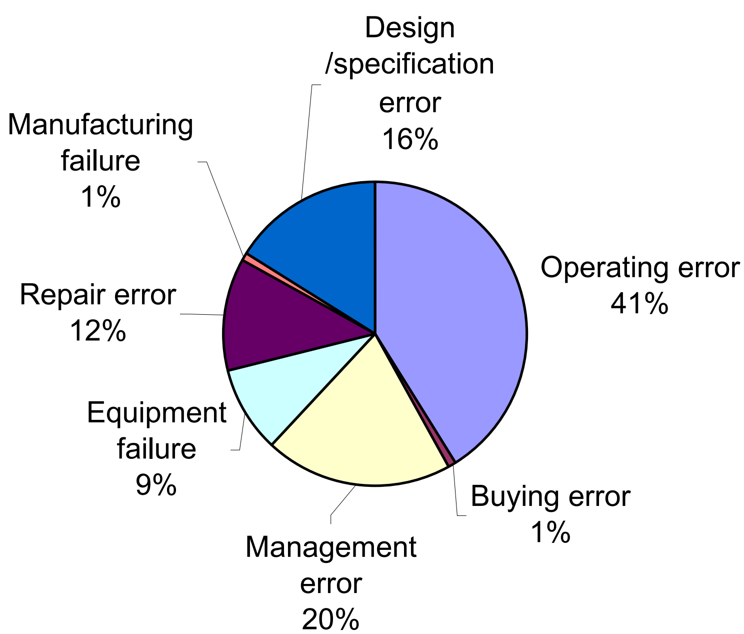

Figure 2.3 Observed product reliability problems (Bradley, 1999)

Therefore, product reliability should be modelled as a function of components, the way that these products are designed and manufactured, and the way that customers and end-users use these products (Brombacher and de Graef, 2001). In this thesis, product-flaw related reliability problems are used to refer to those due to the malfunction of the components and process-flaw related reliability problems are used to refer to those due to the unexpected way of designing, producing and using the products. Based on the discussion, it can be concluded that product reliability depends on both product-flaw related reliability problems and process-flaw related reliability problems.

2.3.2. A Four-Phase Roller Coaster Failure Rate Model

From the discussion in the previous section, it is obvious that the component-based product reliability model should not be used to describe the product reliability behaviour when its basic assumptions do not hold. This is particularly true when developing products under TTM pressure. One of the reasons is that the amount of time that is required by a reliability testing program to remove the infant mortality failures conflicts with the shorter TTM requirement. Special attention has to be given to new technologies, which are not covered by the existing testing programs. Alternate strategies have to be developed to obtain more information about the first phase of the bathtub curve. That is why a lot of research work was carried out to study the genuine behaviour of Phase 1 of the bathtub failure rate curve (Wong, 1988; Brombacher, 1992). Research results have demonstrated that sometimes a four-phase roller coaster curve fits the data better than the three-phase bathtub failure rate curve (Figure 4) for non-repairable products or repairable products before time to first failure. Brombacher (Brombacher, 1992; Brombacher, 1993) proposed a so-called "stressor-susceptibility" concept to explain the four-phase roller coaster failure rate curve. In this thesis, we will use the detailed explanation of the four phases in the roller coaster failure rate from Brombacher and de Graef (2001).

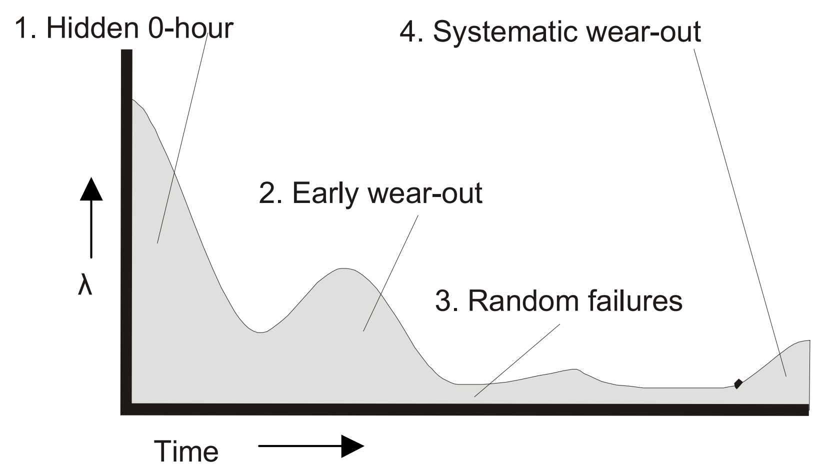

Figure 2.4 Four-phase roller-coaster reliability curve (Brombacher, 1992)

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

- *Phase 2: Early wear-out. Sub-populations of products operating according to specifications but showing, either due to product tolerances and/or tolerances in customer use, deviating behaviour with respect to degradation. This leads to a situation where such a sub-population of products will be reported defective far earlier than the main population.*
- *Phase 3: Random failures. Defects, induced by random events, either internally in the product or externally from customer use or other external influences.*
- *Phase 4: Systematic wear-out. Defects initiated by failure mechanisms in products that lead to systematic degradation of the main population as function of time and/or product use.*

Based on discussions with five high-volume consumer products manufacturers, Lu et al. (2000) observed that under the strong TTM pressure, Phase 1 and Phase 2 of the roller coaster failure rate curve become most critical to these manufacturers. Although this survey was conducted with a limited number of companies in the consumer electronics industry, still a number of interesting conclusions were drawn. Firstly, under strong TTM pressure, it is not possible to perform the complete testing program because this program usually takes too much time. As a result, it is no longer possible to remove all product failures from Phase 1 and Phase 2 before product introduction. Secondly, due to improved technologies, product reliability has improved and thus there are fewer phase 3 problems than before. At the same time, phase 3 and phase 4 problems are economically less important due to rate of technology development, as new products come into the market to replace old ones before the latter reach these two phases. Even if reliability problems from phase 3 and phase 4 do appear, customers also become less bothered because they can always buy a newer product. Customers then perceive reliability problems from Phase 1 and Phase 2 as the product reliability. The fast evolution of personal PCs is a typical example here. PC 286 or 386 can be seen still in use and there is hardly a discussion about the reliability of these PCs even if some reliability problems appear. However, if Pentium Vs have some reliability problems from Phase 1 or Phase 2, it would be reported to Intel very quickly. Thirdly, there is not enough knowledge of Phase 1 and Phase 2 and most of the reliability tests carried out focus mainly on phase 3 or phase 4. Most reliability prediction standards (Jones and Hayes, 1999) are focused mainly on phase 3. From companies' as well as researchers' point of view, more effort should be spent to understand the Phase 1 and Phase 2 of the four-phase failure rate curve. Comparing with Phase 2, Phase 1 is less time dependent (hidden 0-hour failures). They can be both caused by extreme product as well as extreme customer use. Reliability problems from Phase 2 are physically more complicated than those from Phase 1 because the former often relates to degradation and wearout. The definition of reliability problems from Phase 1 determines that these problems can be process-flaw related as well as product-flaw related. This thesis will focus mainly on improving reliability problems from Phase 1 of the roller coaster failure rate curve in fast PDPs.

2.4. Managing Reliability in Fast PDPs

Brombacher *et.al* (2001) identified four PDP structures based on how reliability is managed in the PDPs. These four structures are reviewed and discussed below with close relation to fast PDPs.

- Reactive reliability management

  This type of reliability management is often performed in functional PDPs. In the early 1900s Frederick W. Taylor introduced a new philosophy of production. He proposed to segment a production job into specific work tasks and focus on increasing efficiency in these sub tasks. In doing so, a clear separation is made between managerial and engineering work. Then reliability is the responsibility of inspectors. Reliability is inspected at the end of the production process. Inspection is the primary means to manage reliability. Eventually a separate department is created to be responsible of reliability issues. Other departments then turned their attention to output quantity and efficiency. This type of PDPs is named “Functional PDP” because these PDPs are primarily function oriented (Brombacher et al., 2001). Product reliability problems are present but removed by inspection.

- Interactive reliability management

  This type of reliability management is often seen in sequential PDPs. These PDPs follow the principle of sequential engineering. Therefore they are called sequential PDPs. They are named also as “phased product planning” (Brown and Karagozoglu, 1993), “traditional stage gate process” (Wind and Mahajan, 1997), “phase gate model” (Minderhoud, 1999; Meyer, 1997), etc. Essentially, these processes are performed in a linear fashion, by passing a concept or design from one functional department to another until all the necessary tasks are completed. Reliability management goes beyond inspection and reacts when the output of each phase is not as expected. It focuses on identifying root causes of reliability problems in each phase and taking corrective action to eliminate these problems.

- Proactive reliability management

  This type of reliability management is often coupled with concurrent PDPs. These PDPs follow the principle of concurrent engineering. As a management and engineering philosophy (Godfrey, 1993; Gould, 1992; Hudak, 1992), concurrent engineering requires a systematic, highly integrated and very concurrent way of working among people, technologies, and business processes (Wheelwright and Clark, 1992; Brooks and Schofield, 1995). Development activities are often running in parallel because of one of the most important characteristics of concurrent engineering, i.e., separating the decision-making phase and its implementation phase. Reliability is therefore proactively managed in a concurrent PDP. Potential reliability problems are proactively predicted in the PDP and necessary (corrective) actions are implemented where necessary. Thus all required information has to be available before the PDP starts. With this information downstream problems such as manufacturing difficulties or market mismatch can be well identified and prevented before they happen (Brooks and Schofield, 1995).

♦ Iterative reliability management

This type of reliability management is often seen performed in a dynamic/iterative PDP (Yazdani and Holmes, 1999). These PDPs interact with customers through product prototypes right from the beginning in order to understand better the rapidly changing customer requirements. Therefore, many decisions are initiated and much iteration takes place in the early phase. The process becomes much more concurrent as all activities start at the same time. Information exchange is far more intensive than in a concurrent PDP. Reliability is then managed iteratively along the process, i.e., continuously learning through prediction and quick feedback from customers.

In order to deal with time pressure, a PDP requires very high predictability (Brombacher and de Graef, 2001). It implies that potential reliability problems in such a PDP should be managed proactively, i.e., they should be anticipated and prevented proactively. It is largely because much of the product reliability is determined by the decisions made in the early phases of PDPs (Mortimer and Hartley, 1990; Musselwhite, 1990; Brombacher, 2000). If good decisions on reliability can be made in the early phase of the PDPs, it can save time, reduce rework and improve reliability. On the other hand, decisions can lead to design changes and design changes can significantly influence product reliability. As we know, design changes that are made in the early phases of a PDP can be introduced more easily compared with those changes made in the later phases. However, the influences of the former over product reliability are much higher than the latter (Wheelwright and Clark, 1992). Designers have great flexibility to work with the unfixed design and the cost of that is very low. Late design changes, especially after commercial release of a product, will require changes in an ongoing production process or, even worse, at the customer site, which may cost much more than those early changes

(Business week, 1990). In short, changes should take place as early as possible and reliability should be managed proactively in any PDP under TTM pressure.

Taking those four PDP structures into consideration, it can be concluded that concurrent PDPs and dynamic PDPs are the preferred PDPs to manage reliability problems under strong TTM pressure. As fast PDPs develop derivative products for known markets and known customers, the early iteration encouraged by dynamic PDPs, so as to be more responsive to rapidly changing customer requirements, is not very necessary. These PDPs are mostly recommended for radical products. Examples have been seen in software development as well as in Japanese car industry (Yazdani and Holmes, 1999). Concurrent PDPs are found especially suitable for the development of derivative products with strong time pressure (Eisenhardt and Tabrizi, 1995, Brombacher et al., 2001). The use of mature building blocks and proven technologies from existing products and production processes guarantees the availability of the required information. The incremental characteristics of derivative products make it possible to already optimise reliability early in concurrent PDPs, which enables the following process to run simultaneously and eventually more smoothly and faster. This kind of PDPs is referred to as "concurrent fast PDPs (CFPDPs)" in this thesis. This project thus will focus on improving reliability problems in Phase 1 of the roller coaster failure rate curve in CFPDP.

2.5. Characteristics of Phase 1 Reliability Problems in CFPDPs

The development of the basic idea of concurrent engineering can be traced back to the mid-1980s. There was a growing awareness in American companies that the performances of their PDPs were not matching up to that of their Japanese competitors. Japanese manufacturers were able to produce many products much faster and with better quality. A well-known example was given by Wheelwright and Clark (1994) in the automobile industry. Japanese car manufacturers were able to produce a new auto in about 40 months while their American competitors took approximately 60 months to do so. Hewlett-Packard also reported some startling facts. In testing 300,000 16K RAM chips from three U.S. and three Japanese manufacturers, they found that the Japanese chips had zero failures per 1,000 compared to 11-19 failures for the U.S. chips during the incoming inspection. After 1,000 hours of use, the number of failed U.S. chips was more than 27 (Evans and Lindsay, 1999). Many studies were carried out to research the success of the Japanese and seek for new product development methods. Several studies sponsored by the US government resulted in a new industrial development approach, concurrent engineering. The first definition of concurrent engineering was given by Winner et al. (1988).

Concurrent engineering is a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers from the outset, to consider all elements of the product lifecycle from conception through disposal, including quality, cost, schedule and user requirements.

Concurrent engineering is often considered as a way to change the sequential product development method, especially when dealing with strong TTM pressure. The sequential way of working in a PDP was sometimes called “over-the-wall engineering”. Quite often it reminds people of a relay race where products/design/ideas are passed from group to group in a linear fashion. For example, after market department collects customer requirements, these requirements are passed to development and production engineers to generate the appropriate design and products. Reliability is then managed within the scope of each phase. It is known that fast PDPs deal with very certain and well defined development tasks. This makes it possible to apply sequential PDPs and manage reliability within each phase of these PDPs, even if there is some time pressure (Meyer, 1997; Minderhoud, 1999). However, pushing these processes too hard can result in unexpected reliability problems. This is because initially efficiency can be improved by working harder, but there is a limit. If being faster becomes the only goal and it is achieved by reducing some safety mechanisms like reliability testing simply because they are most of the time very time-consuming, serious reliability problems can occur (Minderhoud, 1999). On the contrary, concurrent engineering is often considered as a rugby race (Meyer, 1997). It requires considerably ongoing interaction between the various business functions involved and is at all times a team effort. Many researchers concluded that concurrent engineering offers companies a better approach to significantly reduce the time it takes to bring products to their customers as well as to substantially improve quality and reduce cost (Takeuchi and Nonaka, 1986; Cleetus, 1992; Dicesare, 1993; Handfield, 1994; Minderhoud, 1999). Typical benefits from implementing concurrent engineering include reduction of TTM and improvement in product quality (Clausing, 1994).

Concurrent engineering has to be viewed at a strategic level in a PDP first in order to reach the expected performance (Kruisak, 1993; Bebb, 1993). It emphasizes the parallel consideration of all aspects of product introduction rather than the more traditional sequential approach. Then a series of disparate tools, techniques and organizational structures can be implemented together to form concurrent engineering (Shina, 1991). Typical solutions include parallel tasks, cross-functional teams, inter-disciplinary workgroups, use of quality engineering method such as Quality Functional Deployment (QFD), Design Of Experiment (DOE), Failure Mode Effect Analysis (FMEA), Statistical Process Control (SPC), and an integrated Computed Aided Engineering (CAE), Computer Aided Design (CAD) and Design For Manufacturing (DFM) techniques. It implies that important decisions have to be made proactively in a concurrent PDP and implementation can happen when necessary. In promoting the separation of the decision phase from its implementation phase, the concurrent PDP is able to generate the expected products. When managing reliability, this means that potential reliability problems are to be predicted proactively, and preventive and corrective actions will then take place when necessary in the concurrent PDP.

As discussed earlier, reliability problems in Phase 1 of the roller coaster failure rate curve are process-flaw related, as well as product-flaw related. Therefore, these two types of reliability problems need to be anticipated and prevented proactively in a CFPDP. Berden et. al (2000) highlighted the fact that anticipation is only possible if enough information of the PDP is available. It implies that when developing a product with dramatic advances in technology and product complexity (a radical product), efforts have to be made even before the development process to obtain information related to product flaws and process flaws so as to ensure product reliability. But it is not the case when developing derivative products. It has long been recognised that concurrent engineering is very suitable to be applied in a fast PDP because only proven technologies and mature building blocks from existing products are used (Eisenhardt and Tabrizi, 1995; Brombacher et al., 2001). As mature building blocks are used from existing products, product-flaw related reliability problems could be already known before the concurrent PDP starts, and therefore can be therefore theoretically fully predicted and managed. In addition, process-flaw related reliability problems could be fully predicted as well because 1) incremental changes in a CFPDP determine that most development tasks are well defined and certain (Eisenhardt and Tabrizi, 1995); 2) derivative products are developed for both known customers and known markets. Thus it is theoretically possible to fully predict and prevent product reliability problems in Phase 1 of the four-phase roller coaster curve in a CFPDP. Expecting such a high degree of predictability leads to formulation of the initial proposition of this thesis.

Proposition: Since a CFPDP employs proven technologies to quickly integrate mature building blocks from existing products, there should be very limited unpredicted Phase 1 reliability problems.

In order to verify whether such a proposition is practically valid, it is necessary to study reliability problems in real life CFPDPs. In the next chapter, results of a field case study are presented.

CHAPTER 3 A CASE STUDY OF A CONCURRENT FAST PRODUCT DEVELOPMENT PROCESS

3.1. Introduction

The purpose of the empirical study that is reported in this chapter was to verify the proposition formulated in Chapter 2, from which the research problem, the research questions and the research objective were identified. Since a case study research relies on analytical generalisation, instead of statistical generalisation, it is not necessary to have a large sample like in a survey research (Yin, 1994, Verschuren and Doorewaard, 1999). The aim of using analytical samples here was not to prove statistically the proposition does not hold all the time, but to demonstrate that the proposition may not hold sometimes. Therefore, a small number of cases should be sufficient. Taking into consideration the constraints in time and resources and the access to a multinational product development company that is active in high-volume consumer electronics industry, it was decided to conduct three cases in this company. Three CFPDPs from three different business units in the company were studied. The results of the first case are discussed in detail in this chapter. The results of the second case are presented in Appendix A. As the case results from the third case are in principle the same as the other two cases, and also for the reason of company confidentiality, they are not included in this thesis.

In this chapter, a description of the business unit at the company where the case study was conducted is given first. The case results are discussed as follows. Section 3.2 describes the relevant characteristics of the business unit such as its products, customers, market position and the characteristics of the product that was chosen for the case study. In Section 3.3, the main phases during the PDP are described. In Section 3.4, the results of testing the proposition formulated in Chapter 2 are presented. Conclusion is given in Section 3.5.

3.2. A Case Study in Consumer Electronics

The company where the case study was conducted is a multinational company, active in the area of high-volume consumer electronics. It has its development centre in both Asia and Western Europe. The business unit in the company where this case study was conducted is active in the area of optical storage. The business unit operates in a business-to-business market, meaning that its customers are other business units of the same company or external companies, not end users. The market for these products shows a strong time and cost pressure. This is also the case for its customers. They operate in competitive market conditions where the short TTM is one of their major constraints. By implementing concurrent engineering, its development cycle has been reduced significantly and its PDP is continuously being adapted to fit the short time scale. Most of its customers introduce three generations of a product platform each year, all with small changes. In order to meet with the requirements of the different customers a lot of derivative products are being developed based upon relatively stable product platforms. In order to maintain the required reliability levels in the final product, customers also demand certain reliability requirements on the performance of the CD Modules.

The product, analysed in this case study, is a CD module with RW compatibility, i.e., it reads from CD-ROM as well as from CD-R and CD-RW. As a derivative product, it has limited minor changes in its features compared to the basic platform architecture, such as:

- The ornamental cover should be compatible with that of the products of 3 well-known Japanese competitors
- A cheaper mechanical motor, which was used to drive CDs, was now used to replace the more expensive motor to drive the sledge in order to reduce cost, i.e., the same motor was used to drive both the sledge and the disks.

Obviously, the main driver to develop such a derivative product was to develop cheaper products with the same functionality as the platform product and this product used the most mature building blocks from existing products. The product was developed in Singapore and produced in Malaysia.

3.3. The Product Development Process

Since the consumer electronics market is currently very mature, the business unit where the case study was conducted has recognised that it requires a rapid succession of new products resulting in ever-shorter development cycles. This can only be achieved if products can be made up of stable, proven technologies and mature building blocks.

This case study is a typical case of such a derivative product. In line with this, the PDP used was structured as a typical concurrent engineering process. Through implementing concurrent engineering, the time of developing a product in the business unit was shortened from two years to half a year. During the case study the business unit had been experimenting with concurrent engineering processes and was in the phase of finalising and documenting a formal CFPDP. Therefore, it had no official written PDP document yet at that time. In order to have a close look at the exact structure of the PDP the project planning process was analysed. From this planning it was possible to derive five main phases: Requirement Phase, Definition Phase, Creation Phase, Industrialisation Phase and Mass Production Phase.

- Phase 1: Requirement Phase. During this phase the feasibility of the project is investigated on the basis of an (study) assignment. The resulting document gives indications for the product market position, market introduction, specification, target cost price, and yearly and total quantity.
- Phase 2: Definition Phase. A number of possible concepts are available for further investigation. A concept is selected, studied and worked out in detail. At the end of this phase a full set of documents supporting the product, its manufacturing process, and its manufacturing equipment requirements are available.
- Phase 3: Creation Phase. Based on the approved documents from the product definition phase the ordering for product tooling is finalised. Line layout, equipment and initial settings become finalised. Samples (using the off-tool parts) are built and sent to customers for evaluation and study. If the evaluation is positive, the team sends qualification samples to customers.
- Phase 4: Industrialisation phase. Production and shipment requirements are prepared. All parts are approved and all tooling is released. At least the first set of moulds and the first production line are realised. After initial production starts up, manufacturing prepares to release more new tooling and moulds, and second or third production lines.
- Phase 5: Mass production phase. The product shall be ready to be introduced to the market. It must be proven that the process is mature and the performance of multiple lines is within acceptable tolerances. The matching of the major components from several tools is also demonstrated.

Besides the major phases of the PDP, various checkpoints were implemented in an executive review process attended by the management. These milestones were approved if a checklist of items was passed. These review phases were called mandatory management milestone meetings. There were nine of them in total: Concept Start (CS), Product Range Start (PRS), Specification Release (SR), Approval Functional Model (AFM), Commitment Date (CMD), Design Release (DR), Industrial Release (IR), Commercial Release (CR), and Mass Production Release (MPR). During each milestone meeting, a formal review of the status of the PDP compared to the original targets of the products' functionality, quality and cost was involved. Pre-established checklists were followed to examine the latest set of development decisions, the success in implementing previous decisions, and the prediction of possible future/downstream problems. If pre-specified criteria were met, the milestone meeting could be successfully concluded, and additional resources could be allocated to the project and various responsibilities could be assigned for the next phase. If, however, the PDP failed at any one of these reviews, it remained in the current phase until the identified problems were resolved and that particular review was passed. Figure 3.1 gives the overview of the structures of the PDP.

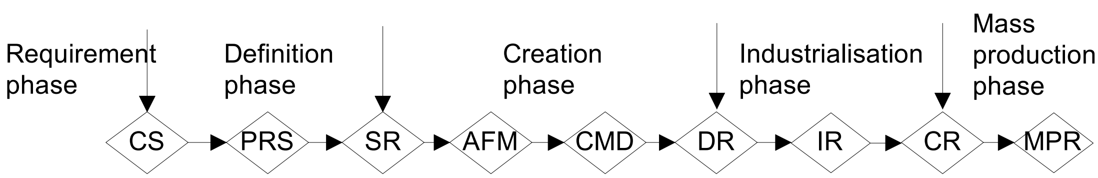

Figure 3.1 Overview of the structure of the PDP at the business unit

Although graphically the PDP is presented as a sequential process, in practice, there was considerable overlapping of the phases. For example, in a fully sequential process, the ordering of tooling starts only after the DR milestone. In this process, it was decided that this action should start before DR in order to follow the principle of concurrent engineering. In order to make it possible, relevant activities that were necessary to enable the early start up of this action were included in the project planning using brainstorming sessions. In short, in order to follow the principle of concurrent engineering, some tasks associated with one phase were allowed to begin in prior phases in order to save time on the critical path of the overall process. In addition, the basic objective of the mandatory management milestone meetings was to keep the project on track, while making risks and trade-offs explicit. This formal review process was intended to encourage cross-functional problem solving throughout the entire process.

The following key observations have been made on the characteristics of the PDP and the product studied at the business unit.

- The PDP studied at the business unit was under increased time-constraint.
- The product was a typical derivative product.
- The PDP studied at the business unit was a CFPDP.

It is therefore suitable to conduct a case study in this PDP.

3.4. The Reliability Problems

There are two sources of information about actual product reliability problems for a business-to-business manufacturer as the business unit: from customers, and from end-users. The Quality Department of the customer reports the reliability problems that happen at customer site to the business unit. Since there are normally standard procedures agreed between the business unit and its customer for collecting and reporting this information, this information is usually communicated between them on a regular basis. The service centre plays a major role in collecting field reliability problems related to the business unit from the end-users. Petkova et al. (2000) showed and explained that many metrics used to measure product reliability from end-users have a strong focus on logistics. The information collection from end-users is often driven by availability, cost and time (Molenaar et al., 2002), but not product reliability. As far as it can be concluded, the nature of the product reliability information from end-users is very different from that of the product reliability information from customers. Compared to the reliability information collected from the customer, the information collected from end-user is much sparser, more complicated, more ambiguous, less accurate and less relevant to the real product reliability problems at this moment. In addition, reliability problems reported by the customer certainly contain early failures that this research project is interested in. Therefore it was decided to analyse reliability information reported by customers in order to draw valid conclusion in verifying the proposition.

As the average portion of the rejected CD Modules at a certain time in a customer factory was recorded and sent back to the business unit, this information was analysed in order to find out whether there were unpredicted reliability problems. Because of confidentiality, detailed case reports will not be discussed here, but necessary important results are discussed below.

Since this product was quickly integrated by using most mature building blocks from existing products, the business unit predicted that there would be less than 0.05% of products reported by its OEM customers with reliability problems. It was observed that the customer rejected 0.2% of CD Modules at the end of the first month in its production, which was four times more than what was predicted. Further failure analysis revealed that 80% of the rejects were due to mechanical noise problems (Figure 3.2). In analysing the returned CD modules, the business unit was surprised by the fact that around 20% of them were actually within the specification. It was found later that the method used by the business unit to measure the noise level was totally different than that used by the customer. The business unit used highly accurate and professional noise measurement equipment while the customer used only trained operators with a simple hand-held meter to judge the noise level. The difference between these two measurement systems resulted in perceived mechanical noise problems.

According to the description of the four-phase roller coaster failure rate given by Brombacher and de Graef (2001), reliability problems from Phase 1 are caused by

♦ Products that are out of specification of manufacturers but are inadequately tested (or have failed after tests) and therefore reach customers

♦ Products that are accepted by the specifications of manufacturers but rejected by their customers due to

- Incomplete specifications of manufacturers
- Mismatch between specifications of manufacturers and their customers.

Obviously the mechanical noise problem is process-flaw related and it is a typical reliability problem from Phase 1. In the CFPDP, mature building blocks and proven technologies were used as much as possible. However, there were still many reliability problems from Phase 1 far beyond the intended target. Therefore, the original proposition, which states that there should be very limited unpredicted reliability problems in CFPDPs, has to be rejected.

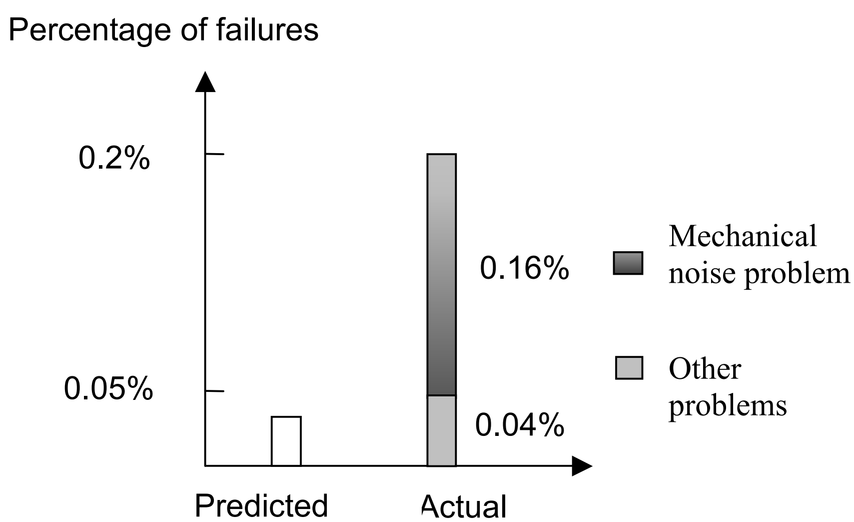

Figure 3.2 Reliability problems of the product

3.5. Conclusion

It has been demonstrated in this chapter that the PDP studied in the business unit is a CFPDP that this research project is interested in. Theoretically, there should be very limited unpredicted reliability problems in the PDP. However, by analysing the customer report, it was learnt that the customer reported many unpredicted Phase 1 reliability problems. The other two cases also show that the major unpredicted problems that were reported by the customer were due to the mismatch between the specification at the manufacturer and its customer, i.e., there were many unpredicted Phase 1 reliability problems in a CFPDP in the other business units. Therefore, it can be concluded that the proposition formulated in Chapter 2 may not hold all the time in the company. As a result, the research problem and the research questions arise:

What causes unpredicted Phase 1 reliability problems in CFPDPs and how can they be prevented?

Research question 1: What causes unpredicted Phase 1 reliability problems in CFPDPs?

Research question 2: How can these problems be prevented?

In the following chapters, further research results will be presented to show how this research project resolved the research problem and answered the research question.

CHAPTER 4 ROOT CAUSES OF UNPREDICTED RELIABILITY PROBLEMS IN A CONCURRENT FAST PRODUCT DEVELOPMENT PROCESS

4.1. Introduction

The earlier study in the company shows that although its CFPDPs is able to integrate mature building blocks from existing products using existing technologies fast, there were still many unpredicted Phase 1 reliability problems observed in these processes at some business units. The three PDPs that were studied in the problem identification phase were considered as the very interesting cases for this research project. It was decided to perform root cause analysis especially for the unpredicted Phase 1 reliability problems in these PDPs.

In principle, the conclusion drawn from the CFPDPs at the three business units were the same. For the same reason discussed in Chapter 3, the results of the first case study are discussed in detail in this chapter, the results of the second case are presented in Appendix A and the results of the third case are not included in this thesis.

The case that is discussed here is the same case that was discussed in Chapter 3. The root-cause analysis of unpredicted Phase 1 reliability problems was performed through analysing reliability information flows in the PDP. The data related to the reliability information flows were collected from relevant archives as well as from formal interviews.

Section 4.2 demonstrates that through analysing reliability information flows in a concurrent fast PDP, root causes of unpredicted reliability problems can be identified. Results of archive data analysis are discussed in Section 4.3 while results of formal interviews are discussed in Section 4.4. Results of combined analysis are presented in Section 4.5. Conclusions are given in Section 4.6.

4.2. Analysing Reliability Information Flows

Ulrich and Eppinger (2000) suggested that a PDP could be described as an information-processing system. It begins with input such as the corporate objectives and capabilities of available technologies, product platforms, and production systems. Then it moves on processing the development information, formulating specifications, concepts, and design details by conducting various activities. Finally, it ends when all the information required supporting production and sales have been created and communicated. Gibson et al. (1988) suggests that when considering an organisation as an information-processing system, the heart of the process is information and the objective is that an organisation effectively receives, processes, and acts on information to achieve performance. Similarly it is possible to consider a PDP as an information-processing system. An information-processing system could be generally considered as a simple open system facing external and environmental (social, political, legal, technical, and economic) boundaries (Gibson et al. 1988). This leads to the well-known simplification of the system that consists of an input, a transformation process and an output.

Input → Transformation Process → Output

Thus, a PDP can be considered as an open system with information as input and output. The core of the PDP, the information transformation process consists of a number of interconnected development activities that transform information inputs into information outputs. Output information from one activity becomes input information for one or more other activities. According to Sander and Brombacher (Sander and Brombacher, 1999), information flows are defined as essential chains of information transformation that are required to operate a business process. In a PDP, different types of information flows exist. Organisation Science researchers have developed many criteria for classifying information flows in a business process. Depending on which particular aspect is to be examined, they include:

- Purpose/function; for example, financial information flows, logistics information flows, and reliability information flow (Guetzkow, 1965)
- Direction; for example, vertical, horizontal, or external (Forza and Salvador, 2001)
- Media richness; for example, telephone, face-to-face or electronic (Daft and Lengel, 1986)

This thesis will view information flows according to their purpose/function. In particular, reliability related information flows would be discussed. The analysis will be based on the MIR concept (Sander and Brombacher 1999; Brombacher, 2000; Brombacher and de Graef, 2001; Knegtering, 2002). The used concept is explained in more detail in appendix B.

As discussed already, reliability is, theoretically, to be proactively managed in concurrent PDPs. Different methods and tools are used in industry for this purpose (anticipate and prevent). By analysing these activities (together with their input and output information) in relation with other related activities, so called reliability information flows can be constructed.

The resulting network can be considered as a reliability information-processing system. It begins with external input such as reliability requirements from customers and end users via a number of tools with either predictive (early) or validating (later) capabilities. This information processing system finally ends with the (dis)satisfaction of the customer with respect to product reliability.

In order to understand the capabilities of a business process in terms of preventing actual reliability problems, the occurrence of field reliability problems can be traced back to the structure of the used reliability information flow and to certain reliability related activities in these information flows. The efficiency of a reliability information flow is not only strongly dependent on the inherent quality of the various activities in the network but also on the quality of the input information. Without a “proper” input, potential reliability problems cannot be predicted properly and it is very well possible to have unpredicted reliability problems reported by customers. On the other hand, when inadequate activities are used in the network, reliability problems are not predicted, prevented and/or mitigated properly, even with proper input reliability information. Therefore, by checking both the quality of the input reliability information as well as the inherent quality of the information processing of these activities, it is possible to identify the root causes of unpredicted reliability problems.

4.3. Results of Archive Data Analysis

Based on the structure of an industrial CFPDP described in Chapter 3, reliability-related activities were identified and a reliability activity model was constructed. Then, based on the input-output relations between these activities, a network of reliability information flows was generated. Related archive data were collected in order to analyse such information flows. These archives include Customer specification requirement, Commercial specification, Technical specification, Production report, Customer report, problem analysis report, corrective action report, milestone meeting minutes, and results of FMEA, reliability tests, and Product Maturity Grid (PMG). When analysing these reliability information flows, three questions were to be answered.

- What was the predicted output of the reliability information flows?
- What was the actual output of the reliability information flows?
- Where (and why) were there differences?

The predicted outputs of these reliability information flows were, initially, derived from project planning documents. By analysing the relevant archives, the actual structure of the information flows was identified. By analysing the input information, the input-output relations as well as the information processing capabilities of the different activities involved, a better understanding of the differences was achieved and the root causes of unpredicted reliability problems were identified. Detailed case results are presented in the following paragraphs.

4.3.1. The Reliability Information Flows and their Predicted Outputs

4.3.1.1. Developing a Reliability Information Flow Model for an Industrial Test Case

In this section for the same case that was studied in Chapter 3, the relevant reliability information flows according to the project planning documents are presented. For this purpose, two steps have been taken.

- Based on the project planning documents, the relevant reliability-related activities in the different phases of the PDP were mapped in a so-called reliability activity model.
- Based on the project planning documents, the communicated information and the communicated structure between these reliability-related activities were mapped and crosschecked; and the resulting reliability information flows were identified.

The results are discussed in the following paragraphs.

4.3.1.2. Reliability activity model

The product, discussed in this case study, is a product that is used as a module in a consumer-electronics product. The business unit discussed in this case study supplies the module to its customer where reliability tests on the module are performed and reliability problems are sent back the supplier. The reliability problems, which were reported by the customer during its test, are considered as the relevant output in this case study.

In concurrent fast PDPs, reliability is to be managed proactively. It means that potential reliability problems are to be identified and managed far before their occurrences. The PDP, analysed in this case study, contains therefore a number of reliability prediction methods to manage potential reliability problems.

One of the main methods used for this purpose was the so-called Failure Mode and Effect Analysis (FMEA). FMEA was used as the main technique to identify potential failure modes and their effects during the PDP. It identifies and, where necessary, removes potential failure modes during different phases of product development. The main objective is to prevent potential reliability problems from reaching customers and end-users. During an FMEA session the following information was generated

- Which components/parts, functions or manufacturing process steps does the product require?
- What are the potential problems related to these components/parts, functions or manufacturing process steps?
- What are the causes of these problems?
- What are their effects?
- What are the severity levels of their effects (weight factors)?
- What are the current statuses of solving them?
- A short description of the solutions and the actions proposed, the responsible person for that action and the expected completion date.

An example of an FMEA worksheet is given in Appendix C.

The major advantage of using FMEA is that it identifies in a systematic manner potential failure modes and their root causes during the early phases of the PDP. In doing so, it stimulates people to think proactively over potential reliability problems and looks for corrective solutions to reduce the consequences of these problems if they cannot be mitigated entirely. According to the project plan used in this PDP, a sequence of FMEAs was used as the main instrument to improve reliability of (purchased) parts, reproducibility of the product, reproducibility of the production process, and product reliability. Corresponding preventive actions will take place when necessary. Preventive action is often in a form of design changes. Late and especially unplanned design changes are known to be very expensive. If something happens, it is more likely to cause reliability problems. Theoretically, the decision to introduce design changes should be made as early as possible and no changes should be introduced after design release. It implies that all potential reliability problems should be anticipated before the DR milestone and after DR, no more new problems should present and only preventive actions should be implemented as planned. Therefore, after SR a first FMEA was executed in order to identify potential reliability problems in the approval functional model; two other FMEAs were done before the CMD and DR milestone to identify potential reliability problems related to product parts and production process steps; an FMEA review was executed before IR. By doing so, the business unit could optimise product reliability step-by-step in the concurrent fast PDP.

Besides the FMEA sessions, three reliability tests were planned. They were to be performed before AFM, CMD and DR. The main objective of these tests were to verify that the product design was mature, that the product would function as specified, that the production process would function as specified, and so on. The reliability activity model for this PDP is shown in Figure 4.1.

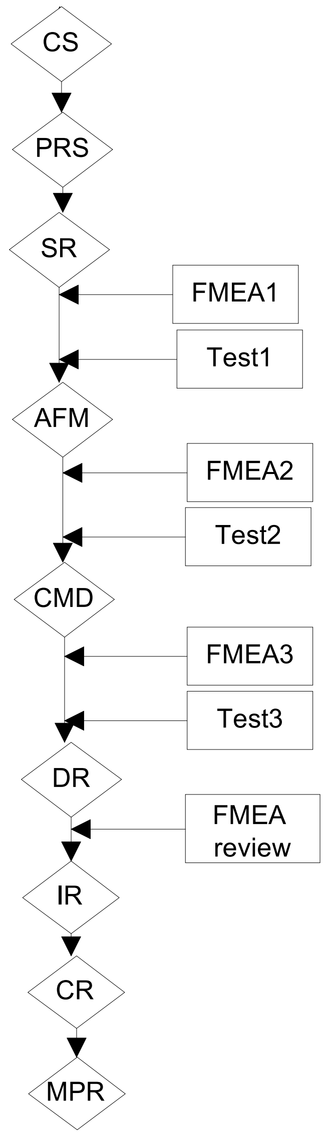

Figure 4.1 Reliability activity model

4.3.1.3. Reliability information flows

The results of FMEA and reliability tests were used to fill up a Product Maturity Grid (PMG). PMGs were used in the milestone meetings AFM, CMD, DR, IR and CR. PMG1, PMG2, PMG3, PMG4, and PMG5 are used here to refer to PMG used at the different milestone meetings. The purpose of these maturity grids was to track the number of open issues (and their severity) in the design of the product and the production process. With this information it was possible to facilitate milestone decisions and to visualize whether the identified open issues are resolved. At milestone AFM, the results of FMEA1 and test1 were used to fill up PMG1. During the PDP the results of FMEA1 and test1 PMG1 were updated continuously. Similarly PMG2 were filled at milestone meeting CMD, with the results from updated FMEA1, updated test1, FMEA2 and test2. Likewise, the results from updated FMEA1, updated test1, updated FMEA2, updated test2, FMEA3 and test3 were used to fill PMG3 at milestone DR. The results of the review of the previous three FMEAs and the updated test results were presented in PMG4 at milestone IR. At milestone CR, the status of the reliability problems indicated in PMG4 were reviewed and further presented in PMG5. Should there be any reliability problems posted in the PMG, action plans with details, e.g. who, when, how and what were documented and presented to the management for decision at milestone meetings. Figure 4.2 shows the developed reliability information flow model.

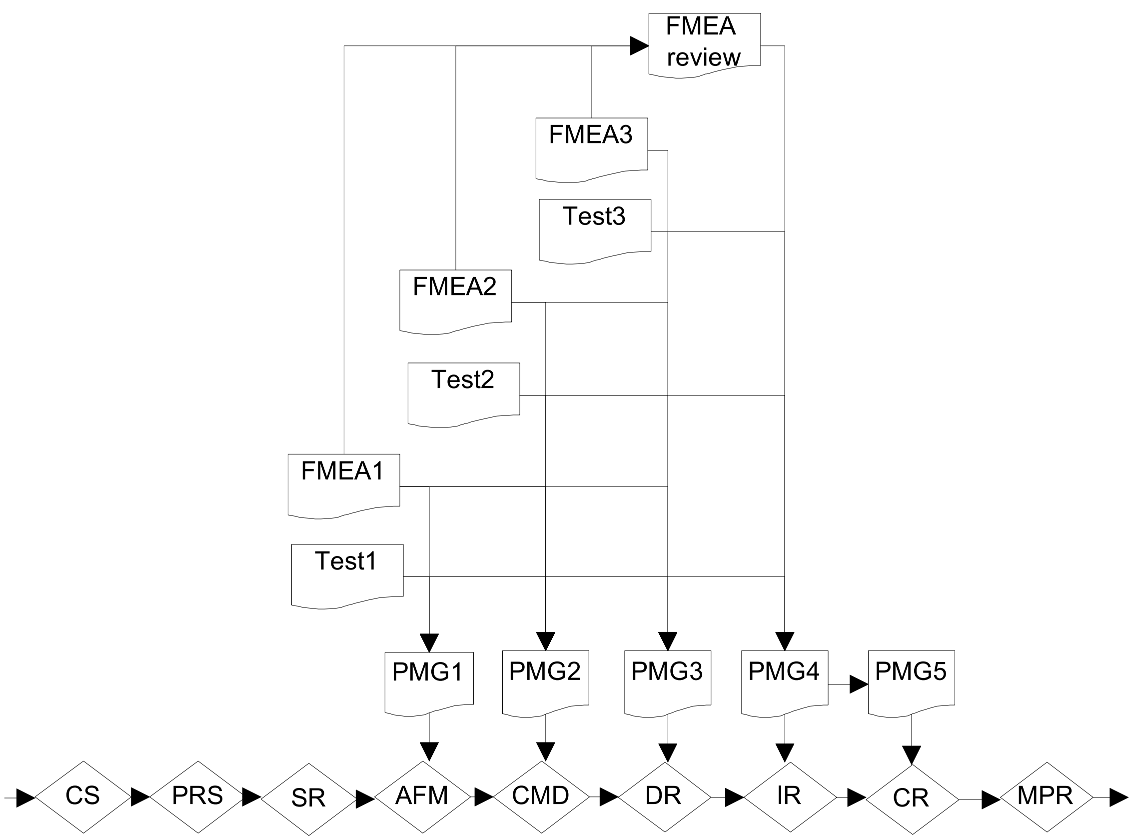

Figure 4.2 Reliability information flow in the PDP

4.3.1.4. Expected output of the reliability information flow

When presenting the results of the PMGs, five gravity factors were used to indicate the severity of potential reliability problems.

- S-problem: non-conformity with safety standard /other safety requirement
- A-problem: a problem that results in a not producible or not saleable product
- B-problem: a problem that results in a product that can be produced but with big problems or will not be accepted by a critical customer
- C-problem: results in a product that can be sold or produced with minor difficulties
- D-problem: problem accepted by management – no activities will be started to reduce or eliminate this problem

A D-problem is often considered as a non-problem. A potential S-problem, A-problem, B-problem, or C-problem is expected to reduce to a D-problem. Besides the gravity factors, there were also five evolution factors used to indicate the (progress) status of potential reliability problems:

- 4: cause not known
- 3: solution not known
- 2: evaluation not yet positive
- 1: solution not yet introduced
- 0: solutions introduced (Generally speaking, if the evolution factor of a reliability problem is greater than 0, it means that this problem is not yet resolved.)

By using five gravity factors and five evolution factors together, the results of a PMG can be presented in a form as showed in Figure 4.3.

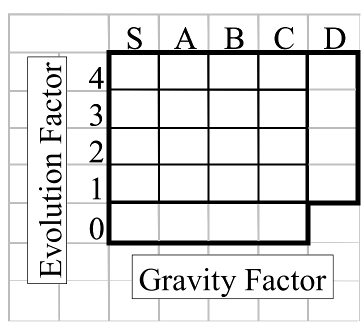

Figure 4.3 Presenting results of a Product Maturity Grid

As discussed earlier, potential reliability problems should be anticipated before the DR milestone and after the DR milestone no more new problems should be identified and only preventive actions will take place when necessary. Figure 4.4 shows the intended results of PMGs at milestone AFM, CMD, DR, IR, and CR. By doing so, potential reliability problems could be managed step-by-step in the PDP. It can be explained in the following way: there should be no unresolved reliability problems in the PMG per above the maturity boundary at the respective management milestone. In a concurrent fast PDP, theoretically, the predicted results of FMEA and reliability tests at these milestones should follow a reliability growth pattern as shown in Figure 4.4.

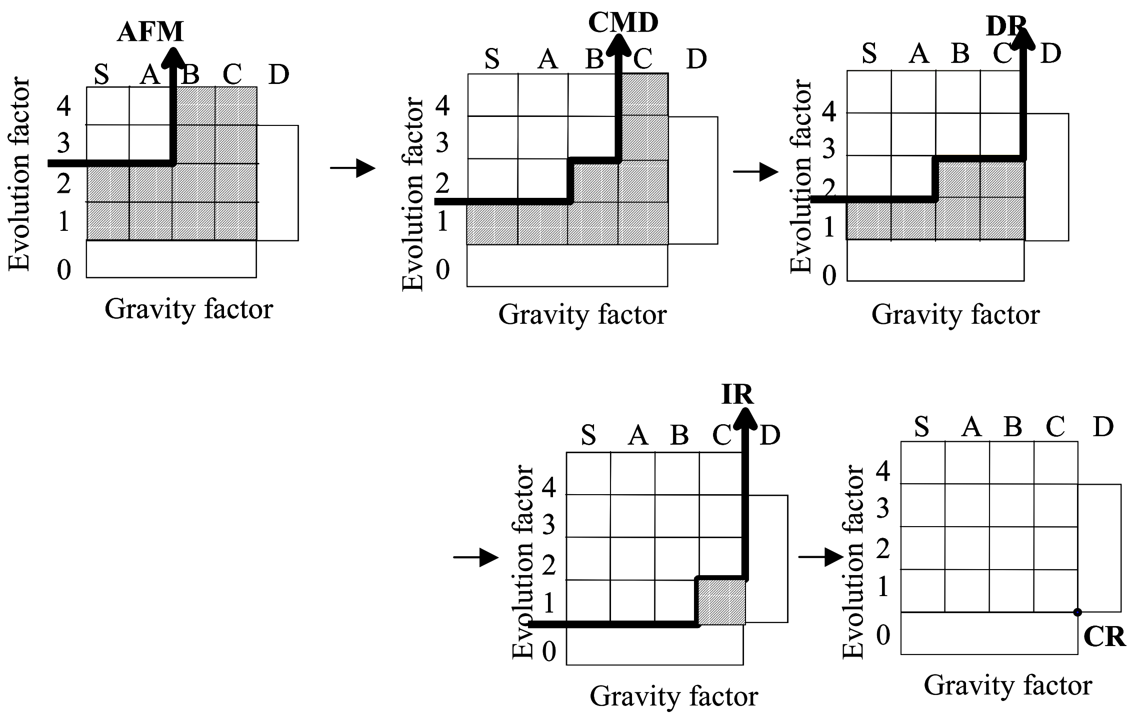

Figure 4.4 Intended results of PMG from AFM to CR

As shown in Figure 4.4, at the CR milestone, there should be only reliability problems of S0, A0, B0, C0, D1, D2 and D3 left. It implies that all S, A, B and C type of reliability problems have to be resolved before the CR milestone and the only open problems are type D problems that are accepted by management and no activities will be started to reduce or eliminate these problems. For example, when developing a product, a cheap component is used for the purpose of cost reduction and it is known that there will be product failures due to this cheap component. As saving cost is the main driver for using this cheap component, the management decides to accept these failures. Then no further action will be taken to reduce these failures.

Based on the reliability performance of the building blocks from existing products and the integration process, the business unit predicted that there would be a certain percentage of failures due to type D problems after the CR milestone and it decided to accept them so that no further actions were taken to resolve them. Therefore, the business unit predicted that there would be less than 0.05% product failures reported by customers.

4.3.1.5. The actual output of the process in the field

The previous sections have discussed how, in theory, PMGs can be used to manage reliability in a CFPDP. In order to see whether an actual CFPDP is able to follow this line, this section presents an actual set of PMGs observed during the case study. PMGs from AFM till IR as well as the customer report are shown to identify the differences between the predicted results and the actual results, both in a qualitative and in a quantitative manner.

PMGs at AFM, CMD, DR, and IR were collected. They are presented in Figure 4.5. Through comparing Figure 4.5 and Figure 4.4, it was observed that the actual results of PMGs did not meet the prediction. At milestone IR, there were still 3 A4 problems, 7 B4 problems, 2 C3 problems, 1 A1 problem, 1 B2 problem and 1 B1 problem unresolved. To resolve these problems before the CR milestone was then not quite possible. As studied earlier, the customer report further indicated the existence of unpredicted reliability problems. 0.2% instead of 0.05% product failures were reported and 0.16% of them were due to mechanical noise problem. It could be concluded that the actual outputs of the reliability information flows were far away from the predicted results both in pattern and in value.

4.3.2. Analysing Differences Between Predicted and Actual Performance

Comparing predicted to actual field performance, the achieved product performance was not as good as predicted and there was a considerable amount of unpredicted Phase 1 reliability problems reported by the customer. Thus the results of the FMEAs and reliability tests were analysed in detail, especially for the unpredicted reliability problems. In this way, a better understanding was achieved of what caused unpredicted Phase 1 reliability problems in the PDP. Results are presented below.

The intended results of PMGs from AFM to CR imply that in the PDP, theoretically, potential reliability problems should be predicted, resolved or accepted by the management. In return, the customer should report very limited unpredicted reliability problems. Therefore, in theory, there would be one type of reliability problems in the

PDP. They are "Proactively Managed Problems (PMP)". PMP refer to those problems that are predicted and resolved or accepted in the PDP.

However, it was learnt that there were many unpredicted reliability problems. By analysing the detailed results of FMEAs and reliability tests in connection with unpredicted reliability problems, besides PMP, three other categories of reliability problems were identified. They are presented in Figure 4.7. In the following paragraphs, the four groups of reliability problems are discussed in detail.

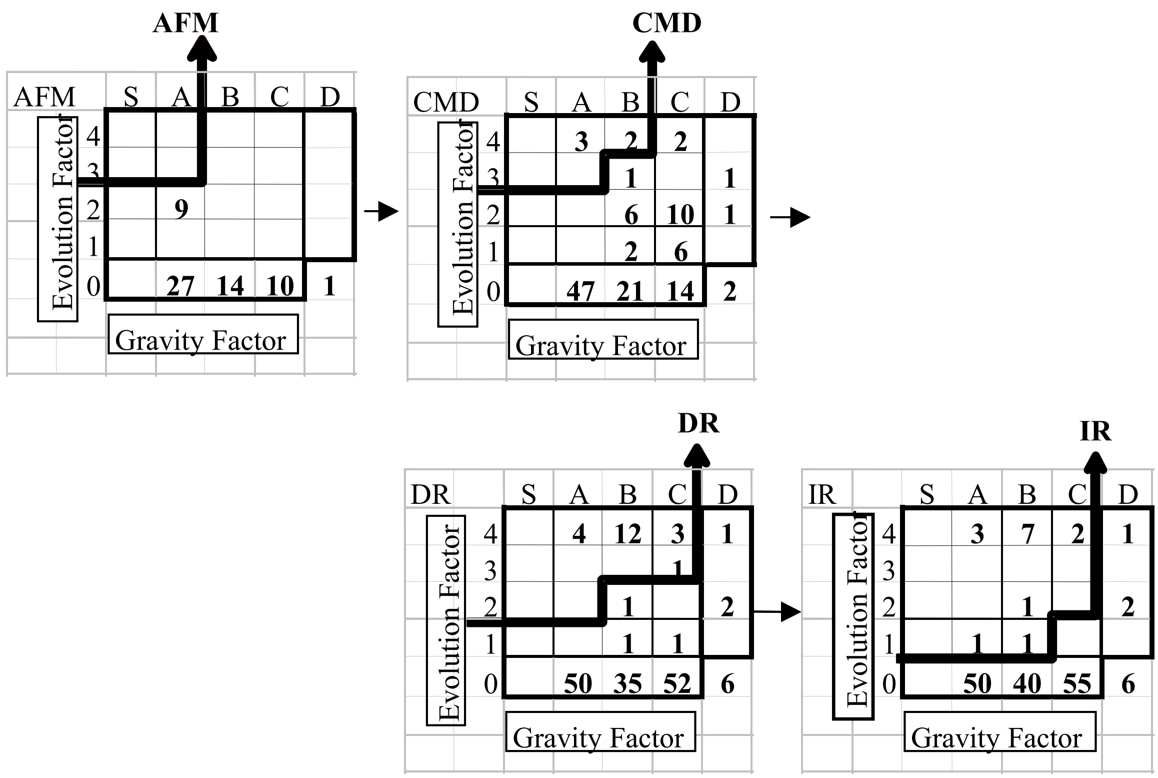

Figure 4.5 Observed PMGs at AFM, CMD, DR and IR

♦ "PMP"

These problems were proactively identified and resolved by FMEAs before their occurrences and consequently the customer did not report them. For example, actuator operating at 60 degree C due to request for specification change from customers was predicted in FMEA2 based on experiences from other products. It could be fixed by adjusting the relevant specification. After a quick verification by Engineering personnel, it was resolved and closed by DR. Therefore it was not reported by the customer. The reason that such a problem was proactively prevented in the PDP was that all the information required to identify this problem was used even before such a problem appeared and preventive actions were also taken accordingly to prevent this problem.

♦ "Noise problems (NP) "

These problems were identified by FMEA, but they simply disappeared without any actions after that, and the customer did not report them. Dynamic behaviour caused by no glue was a typical example in this group. It was identified by FMEA1 and remained unresolved but it was not mentioned any more and the customer also never reported it. It was learnt that these problems were in fact irrelevant product reliability problems. The input information used in predicting them was irrelevant to product reliability. After these problems were identified, the business unit most of time forgot why these problems were identified and they were simply neglected. Fortunately and surprisingly, the customer never found these problems. In short, because relevant reliability information was not always used during FMEA sessions, these problems appeared. They would exist continuously as long as the relevancy of the input information remained unimproved. They could be certainly prevented if the relevant reliability information was used by FMEA. Figure 4.6 shows an example of such problems NP in FMEA1.

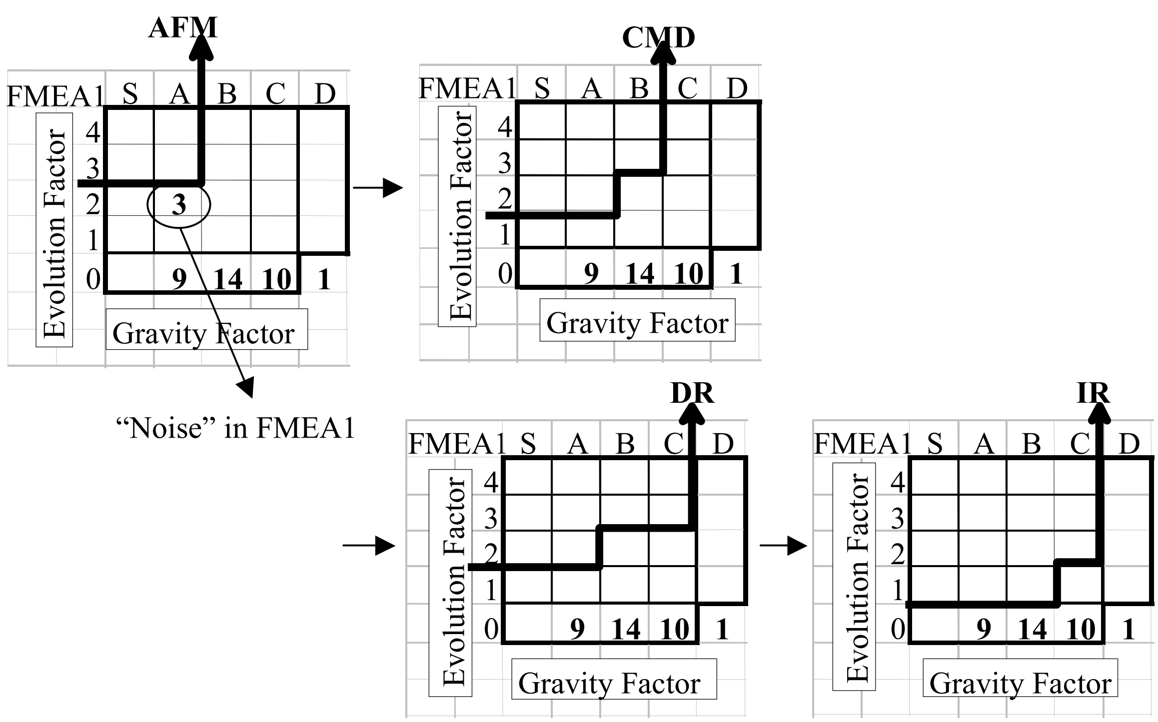

Figure 4.6 Example of " Noise Problems"

- "Reactively Managed Problems (RMP)"

  These problems were identified by FMEA in the PDP initially as product-flaw related problems although they were actually process-flaw related. Later in the PDP, they actually occurred as process-flaw related problems. They were resolved by negotiating with the customer. In the end the customer did not report these problems. Dc-offset problem was a typical example of this group. The CD-RW compatibility was a strong selling feature and this requirement was stated in the Customer Requirement Specification from the start. The CD-RW feature had implications on the dc-offset of the operational amplifiers used to convert the current to the voltage form of the signal. It is known that the signal to noise ratio for CD-R is high while that of CD-RW is unacceptably low due to the constant dc-offset. It was planned that CD-RW compatibility was to be introduced after the CMD milestone. Therefore, the functional model at the AFM milestone, which was supposed to have all the features of the final product, did not have a CD-RW feature. The specification of dc-offset was still used from the CD-R feature. However, early FMEA (FMEA1 and FMEA2) did not use this information to predict dc-offset problem as a potential reliability problem and thus no actions were taken to prevent dc-offset problem. After the CMD milestone, FMEA3 just realised that dc-offset could be a potential reliability problem. The business unit considered the laser diode circuit to be responsible for the dc-offset problem and requested the supplier to make necessary adjustment. However, the operational amplifier was ordered already and it was too late to make any design changes at the supplier site, the only possible solution was to negotiate with the customer so that they could relax the requirements on dc-offset. The problem was finally resolved after several stages of negotiations with the customer to increase the allowable dc-offset. Eventually it was not reported in the customer report. Obviously RMP could be potentially prevented if the required information was used at the right moment in the PDP to predict these problems proactively.

- "Poorly Predicted Problems (PPP)"

  These problems were identified by reliability tests first in the PDP as product-flaw related problems although they were actually process-flaw related. The customer later reported them as unpredicted reliability problems, namely the mechanical noise problems. The business unit initially considered that the cheaper mechanical motor, which was introduced as part of the derivative changes, was mainly responsible for the mechanical noise problem. Compared to the more expensive motor used in the platform product, this motor could operate at a higher speed but generate more noises when driving the sledge. However, its specification was copied from the more expensive motor. That was why the mechanical noise problem was first identified by reliability test1. As this motor was considered as a mature component and taken from other products, its reliability was already determined outside the PDP. The business unit could only introduced a simple solution (adding grease) to reduce the mechanical noise problem. However, this was simply not a root cause level solution and it worked only occasionally. That was why the mechanical noise problem was predicted by FMEA2 and indicated as a resolved problem later, but it was again identified by reliability test2 and reliability test3 and remained unresolved. The business unit then had to negotiate with the customer to relax the specification. That was why the mechanical noise problem remained unresolved in the PDP. On the other hand, the business unit used highly accurate and professional noise measurement equipment while at customer site trained operators used a simple hand–held meter to judge the noise level. It was learnt that the business unit was aware of such information since the customer used the same method to test mechanical noise problem on other CD modules and related mechanical noise problems were caused before. Because such information was not used in reliability prediction the mechanical noise problem was reported as the unpredicted reliability problems.

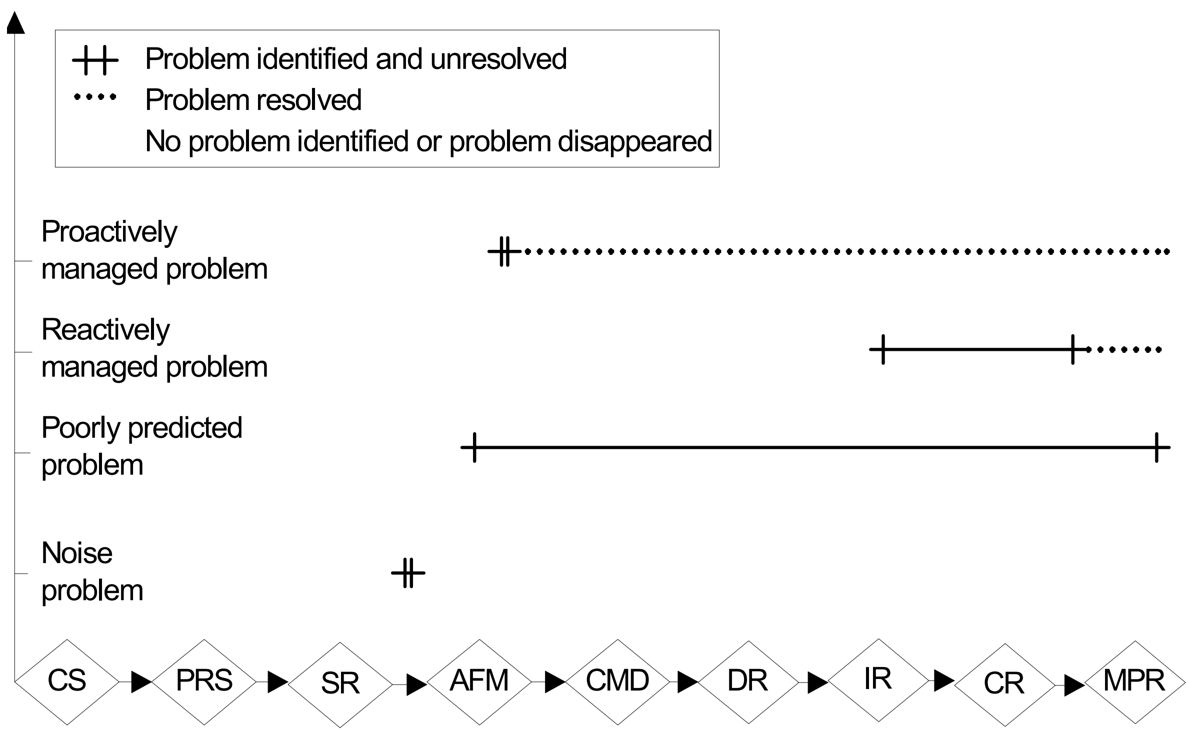

Figure 4.7 Different types of reliability problems managed in the PDP

4.4. Results of Formal Interviews

As discussed earlier in Section 4.2, in a CFPDP, unpredicted reliability problems are always associated with the outputs of a number of reliability-related activities. By analysing the input information as well as the information processing/deployment connected with these activities, i.e., analysing reliability information flows, root causes of unpredicted reliability problems can be identified. According to (Brombacher, 1996; Sander and Brombacher, 1999), the Maturity Index on Reliability (MIR) concept can measure the quality of the information flow as well as the information deployment along a business process. It has been widely applied to assess the maturity of reliability information flows in PDPs at a number of American, European and Japanese companies that operate in high-volume consumer electronics industry, medical industry, and chemical industry. It can be applied to organise formal interviews to

- ♦ analyse and model the information flows within a PDP
- ♦ measure the quality of the information along a PDP
- ♦ establish relations between product reliability and the structure of the information flows

In order to verify and enhance the results of archive data analysis, formal interviews using the MIR concept were conducted to analyse reliability information flows related to unpredicted reliability problems. As presented by Knegtering (Knegtering, 2002) an MIR analysis can reflect the capability of an organisation in analysing, predicting, improving reliability of its current and future products. As this research project was particularly interested in root causes of unpredicted reliability problems, obviously the MIR analysis generated more than what was necessary. Due to the agreed confidentiality with the company, the resulting MIR report will not be discussed here and only the relevant results are discussed below. The detailed steps in an MIR assessment to identify the reliability information flows are presented in Appendix B.

One of the characteristics of an MIR analysis that needs to be stressed here is that multiple sources of evidence are used during the interviews. People involved in the reliability-related activities in the PDP (described in Chapter 3) were invited for interviews. During the interviews, two levels of verification were done. One level was done between two different connected activities. The input to the subsequent activity always had to be verified with the output of the current activity. The other level of verification was performed within one activity between managers and engineers (retrospective). Through multiple sources of evidence, a better understanding could be achieved of what the current activity generated and what was required for the subsequent activity could be achieved. Therefore, 17 employees involved in the PDP, including 9 managers and 8 engineers, from Marketing Department, Development

Department, Engineering Department, Production Department, Quality Department, were interviewed. Table 4.1 displays how the interviews were organized: the number of the interviews, the level of the interviews and the duration of the interviews. Detailed results are discussed below.

Table 4.1 Description of interviews

Main stream product	Total interviews	Manager level interviews	Engineer level interviews	Duration per interview
CD Module	17	9	8	½ hour

The quality department was, in this case, the main source of feedback information. Theoretically, in the concurrent fast PDP, there should be a weak relation between the results of reliability tests and FMEA on one hand and the reliability problems reported by the customers on the other hand, especially when the actual problems are way beyond target. This is because reliability problems identified by FMEA or reliability tests should have been resolved or prevented before the customer found them. However, what was observed was quite different. Two different groups of reliability problems could be distinguished.

The first group of problems was identified by FMEA but not reported by the customer. Within these problems three different groups were further distinguished:

- ♦ Reliability problems identified by FMEA and resolved immediately after the implementation of corrective actions. Thus the customer did not report these problems.
- ♦ Reliability problems identified by FMEA. However, without any follow up action (corrective action), these problems disappeared and had no relation with reliability problems reported at customer sites. It was observed that the information that was used to identify these problems was irrelevant to actual product reliability.
- ♦ Reliability problems identified by FMEA as product-flaw related problems but they occurred in the PDP later as process-flaw related problems. They were finally resolved by negotiating with the customer. It was learnt that the required information to identify these problem early in the PDP was known but not used when necessary.

The second group of problems showed a high relation between the results of FMEA and reliability tests and the reliability problems reported by the customer. They were in fact the unpredicted reliability problems, namely mechanical noise problems. These problems were identified first in the PDP because of the reliability of the mechanical motor. As this mechanical motor was taken from another CD module, within the PDP, efforts were made just to reduce not to resolve the mechanical noise problem. Mechanical noise problems reported by the customer was caused by the different ways of testing mechanical noise at the business unit and at the customer. Although this information was available in the business unit, it was not used to predict the mechanical noise problem. Therefore, no matter how hard the business unit tried to reduce the mechanical noise problem in the PDP, it was still reported by the customer as an unpredicted reliability problem.

4.5. Combined Analysis

The results of the archive data analysis and the formal interview analysis showed the same conclusions. It was learnt that information that should be used to proactively manage reliability problems in this concurrent fast PDP was known to the business unit, but it was not used at the right moment in the PDP. As a result, RMPs and PPPs happened and the customer later reported PPPs as unpredicted reliability problems. Typical reliability problems identified in the PDP are displayed in Table 4.2. Obviously, if RMPs do not happen in the PDP, it would be highly possible that they also become unpredicted reliability problems reported by the customer. When irrelevant information was used in reliability prediction, NPs occurred. Potentially, they (RMP, PPP and NP) could be proactively managed if the required information was used at the right moment in the PDP. It can be concluded that these problems were not due to the poor designed product parts or components, or due to poor communication between the customer and the business unit as it did have all the required information in the process; they are due to the fact that the required information was not used at the right moment in the process or the information was used but incorrectly.

Table 4.2 Typical reliability problems in the PDP

Reliability problems identified in the PDP	Relation with customer report	Examples
PMP	No	Motor failure due to flux going into coil
NP	No	Dynamic behaviour due to no glue
RMP	No	Dc offset
PPP	Yes	Mechanical noise problem*
* Unpredicted problems in customer report		

4.6. Conclusion

4.6.1. Reflection on Research Question 1

According to the proposition, presented earlier, unpredicted reliability problems should not occur in a CFPDP since such a PDP uses most mature building blocks from existing products and proven technologies. In this type of PDP, reliability management could be an optimisation process of selecting and adapting known building blocks. The methods and tools used by the business unit in this analysis seem very well suited for this task. However, it was found during this research project that reliability management did not follow this pattern and that unexpected problems still occurred.

From the case study, it was learnt that the mechanical noise problem could be potentially predicted if the information about the way of testing mechanical noise at customer site was used when making the reliability prediction. Although the information was available in the PDP, it was not used at the right moment in the PDP. Obviously the way that the customer used to test the mechanical noise level was not as elegant as the way that the business unit used. However, what mattered was not about how mechanical noise was professionally tested at the business unit but about whether it was tested in line with the customer. Therefore, it can be concluded that under TTM pressure there should be very limited unpredicted reliability problems in a CFPDP in case the information required to predict and prevent reliability problems is used at the right moment in the PDP. Galbraith (1973) defined uncertainty as “the difference between the amount of information required to perform a task and the amount of information already possessed by the organization”. Such form of uncertainty did not exist in the CFPDP that was studied, as all the required information was already available. However, there is a different form of uncertainty observed in the case study. Therefore, uncertainty in reliability prediction is defined in this thesis as “the difference between the information used to predict reliability and the information required to predict reliability”. When the difference does exist, the information used to predict product reliability becomes the uncertain information. In a CFPDP, the important matter is not to get more information but to reduce the uncertainty in reliability prediction. When predicting reliability using uncertain information, the resulted prediction consists of the potential reliability problems, their probability of occurrences, and the uncertainty in making such prediction due to the uncertainty in reliability prediction.

In addition, it was observed that unpredicted reliability problems caused by uncertainty in reliability prediction were not unique to the CFPDP that was studied and it was also not unique to the business unit. Similar problems happened also in other business units in the same company. Appendix A also shows how uncertainty in reliability prediction caused unpredicted reliability problems in a CFPDP in the other business unit.

Therefore, it can be concluded that unpredicted Phase 1 reliability problems were caused by uncertainty in reliability prediction.

Those unpredicted reliability problems could certainly happen in other types of PDPs as long as the information that will be used remains uncertain. For example, given a platform product or breakthrough product, if the same mechanical motor is used and the mismatch between the test specifications over mechanical noise level remains unresolved, it is certain that mechanical noise problem can occur to this product as well. However, they can potentially be predicted and prevented if the available information is used.

4.6.2. Reflection on how Reliability Methods were Used when Making Reliability Prediction

Based on the case results, a few important observations are made about the way that FMEA used the information to make a prediction when the information was uncertain.

- FMEA was able to predict PMP because the business unit had all the required information and it used this information proactively to predict PMP. Necessary corrective actions were also taken to prevent them from appearing in the customer report.
- FMEA was not able to differentiate the irrelevant information from the relevant information when predicting potential reliability problems and thus NP appeared in the PDP.
- FMEA was not able to predict RMP properly as the required information was not used when predicting potential reliability problems although the business unit had this information already. Furthermore, it is very likely that RMP would become unpredicted reliability problems reported by the customer if this information were not used in the end to negotiate with the customer.
- FMEA was not able to predict PPP and prevent unpredicted reliability problems because the required information was not used when making prediction.

In short, FMEA was not able to differentiate uncertain information from certain information and therefore was not able to use the right information properly. As a result, unpredicted reliability problems appeared. In order to prevent these problems from reoccurring, a solution is proposed in next chapter.

CHAPTER 5 DESIGNING A RELIABILITY PREDICTION METHOD IN CONCURRENT FAST PRODUCT DEVELOPMENT PROCESSES

5.1. Introduction

FMEA is a popular approach to anticipate and prevent failures by designing them out of products and processes. Theoretically, in concurrent fast PDPs, reliability problems should be identifiable to a very large extent. However, as discussed in the previous chapter, when reliability information is uncertain, i.e. it is not adequately deployed, Phase 1 reliability problems cannot be properly predicted and prevented by using FMEA. Research question 2 therefore becomes

♦ Is it possible to define a method to predict product reliability in CFPDPs including aspects of uncertainty?

In Section 5.2 the formal requirements to be met by such a reliability prediction method are identified. Necessary building elements to fulfil these requirements are discussed in Section 5.3. Section 5.4 a design is proposed to fulfil the identified requirements, followed by giving a detailed description of the proposed method, Reliability and Quality Matrix (RQM). In Section 5.5, the relation between RQM and QFD is discussed. The relation between RQM and FMEA is also discussed in following section. Conclusions are given in Section 5.7.

5.2. Formal Requirements for a Reliability Prediction Method

CFPDP develops products by quickly integrating product parts (mature building blocks) from existing products using proven technologies. Compared to existing products, these products use the same or closely related derived mature building blocks. The only difference is that some changes have to be introduced when integrating these parts together. For example, in order to integrate two different parts together, the existing design values or dimensions may be modified. These changes are based most of time on proven technologies and considered as part of the derivative changes. Theoretically decisions are already made upfront in the PDP on which product parts and production process steps from existing products and production process will be used and what changes must be made in order to fulfil customer requirements. Consequently, relevant reliability problems can also be predicted and prevented. Thus, these reliability problems can be considered as reliability risks. As severity and probability of occurrence are often used to characterise risks in risk management (Williams, 1993), they are also used in this thesis to characterise potential reliability problems.

As demonstrated in the previous chapter, by using FMEA it is not in all cases possible to predict and prevent potential reliability problems when the reliability information used is uncertain. Therefore, an alternative method, which enables predicting and preventing potential reliability problems in CFPDPs also with uncertain information, is needed. This method should meet all four related requirements listed below.

Requirement 1: Classifying uncertainty when predicting potential reliability problems

As discussed in Chapter 4, by using reliability methods such as FMEA the team failed to differentiate uncertain information from certain information when predicting reliability. As a result, many unpredicted reliability problems were observed in the case study. In order to prevent and manage such problems, it should be possible to recognise the higher degree of uncertainty in the information when predicting reliability by using the new method. As a result, potential reliability problems (risks) should be characterised by three dimensions: severity of the problem, probability of occurrence and last but not least uncertainty in the used information.

Requirement 2: Prioritising uncertainty improvement activities

Smith (1999) suggested that when the product development schedule shrinks, managing potential risks should focus on reducing their probability of occurrence. However, as learnt from Chapter 4, when the information used for predicting reliability is uncertain, reliability problems cannot be managed by using FMEA that focuses mainly on reducing their probability of occurrence. The method to be developed should focus on reduction of uncertainty as a first step in order to be able to prioritise improvement actions based on substantial information.

Requirement 3: Managing uncertainty in CFPDPs

When a CFPDP progresses, even without any actions to manage uncertainty, uncertainty decreases towards the end of the process since there is increasingly accurate field information available (curve a in Figure 5.1). However this can be too late for the PDP. In the case study it was observed that many product reliability problems were identified very late in the PDP and some of them became even unanticipated Phase 1 reliability problems at the customer when uncertainty in reliability information was neglected during the process. In a CFPDP, theoretically, reliability is to be managed proactively. It requires that the degree of uncertainty in reliability prediction be reduced very early in the PDP (curve b in Figure 5.1). After that it should still be possible to manage the predicted reliability problems proactively. Therefore, it is important to known whether the degree of uncertainty indeed decreases and how it decreases over time. By using this method in the PDP, it is then possible to monitor and manage the degree of uncertainty as a function of time.

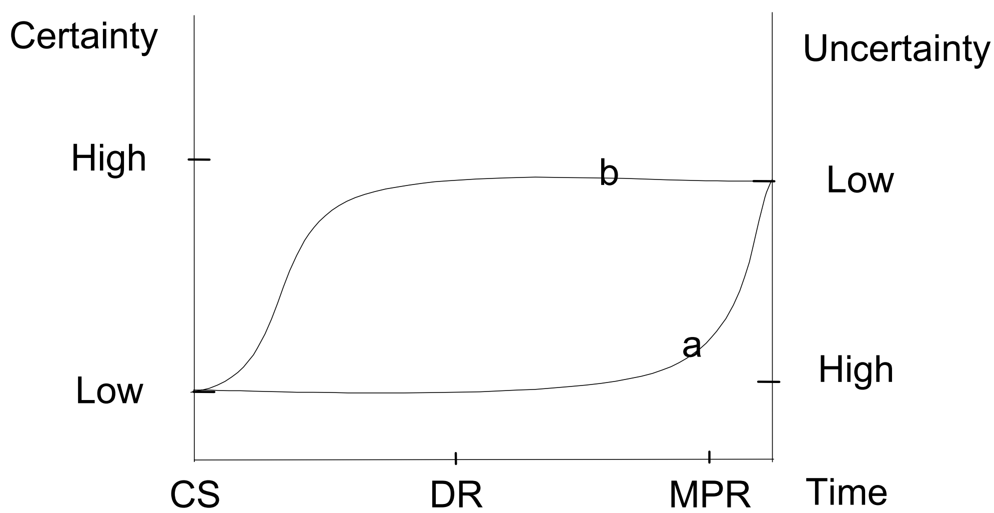

Figure 5.1 Managing uncertainty in a PDP; a) no management; b) pro-active management

Requirement 4: Optimising product reliability in CFPDPs

As demonstrated in Chapter 4, by using FMEA it was not possible to predict all potential reliability problems in CFPDPs. As a result, product reliability cannot be optimised in the PDPs. Since a CFPDP requires reliability optimisation, especially in the early phases of the PDP, the “to be developed” tool should have provisions for early reliability analysis in such a manner that product optimisation becomes possible.

Among the four requirements discussed above, requirements 1, 2 and 4 are method related (the functionality that the method should have) while requirement 3 is process related (the way that the method should be used). Based on these requirements, a method called Reliability and Quality Matrix (RQM) was developed. An Excel-based spreadsheet is developed to structuralize the information collected during the different phases of a CFPDP on the criteria mentioned above. In the following section, the building blocks to solve the requirements are discussed first. The detailed description of RQM is described next.

5.3. A Proposal for a Design to Meet the Formal Requirements

5.3.1. Method-related Requirements

Classifying uncertainty

Based on the definition given by Brombacher and de Graef (2001), reliability problems from Phase 1 of the four-phase roller coaster curve can be process-flaw related or product-flaw related. Process-flaw related problems are often accepted by the specifications of manufacturers but rejected by their customers due to incomplete specifications of manufacturers or mismatch between specifications of manufacturers and their customers. Product-flaw related problems are problems related to products often being out of specification of manufacturers but inadequately tested (or have failed after tests) and therefore reach customers.

As CFPDPs rely on fast integration of mature building blocks using proven technologies, potential reliability problems can be predicted associated with product parts (building blocks) and production process steps in RQM. Theoretically, there is one type of information that can be used in reliability prediction in such PDPs. That is the information from existing products (related to product parts) and production processes. In Chapter 4, uncertain information was found as a cause for failure of reliability predictions resulting in unpredicted Phase 1 reliability problems. Because of this, information used in reliability prediction should be classified into two different uncertainty levels. The first level of information is called “certain” and the second level is then called “uncertain”. As a result, these two uncertainty levels can be used to distinguish uncertain information from certain information.

- Uncertain. Uncertainty level due to using uncertain information. This type of information is mostly based on “rule-of-thumb”.
- Certain. Uncertainty level due to using certain information. This type of information is from existing products and production processes.

When using certain information to estimate the probability of occurrence of a potential reliability problem, it is to be directly copied from the existing products and production processes. This estimate is therefore considered as a “validated estimate”. The uncertainty level in such prediction is very low. When using uncertain information to estimate the probability of occurrences, the estimation is also uncertain. As a result, the estimation of probability of occurrence is also classified into two groups by using the method according to the degree of uncertainty involved in the estimation.

- Rough estimate. When uncertain information is used to estimate the probability of occurrence of a potential reliability problem, such estimation is considered as "rough estimate".
- Validated estimate. When certain information, i.e., information from trial run, from existing products and production processes, is used to estimate the probability of occurrence of a potential reliability problem, such estimation is called as " validated estimate"

During the development of the method, one more type of estimation was recognised. When incremental changes have to be introduced to production processes and/or product parts to fulfil certain customer requirements, computer simulations or real experiments are used to estimate the probability of occurrence of associated potential reliability problems. Compared with the other two types of estimation, the uncertainty level of this estimation is in between. It is more certain than the rough estimate but less certain than the validated estimate. Thus, it is considered as a "model-based estimate" and its uncertainty level is "medium certain". As a result, the estimation of probability of occurrence is further classified into three groups by using the method according to the degree of uncertainty involved in the estimation.

- Rough estimate. When highly uncertain information is used to estimate the probability of occurrence of a potential reliability problem, such estimation is considered as "rough estimate".
- Model-based estimate. When the information of computer simulations or real experiments is used to estimate the probability of occurrence of a potential reliability problem, such estimation is called as " model-based estimate".
- Validated estimate. When the very certain information, i.e., information from trial run, from existing products and production processes, is used to estimate the probability of occurrence of a potential reliability problem, such estimation is called as " Validated estimate".

Prioritising uncertainty improvement activities

When using very certain information to make a prediction, this method does the same as FMEA, i.e., it focuses on reducing the probability of occurrence so as to prevent potential reliability problems. When less certain information is used in reliability prediction, this method should concentrate on reducing uncertainty first. Failure probability reduction is irrelevant at that time. It will be only considered when necessary after the uncertainty has been reduced (Table 5.1).

Optimising product reliability

This method identifies what derivative changes need to be made to product parts and production process steps, which are taken from existing products and production process steps in order to meet customer requirements. Consequently, potential reliability problems related to these product parts, production process steps, and necessary changes can be predicted and optimised. To do so, this method first prioritises customer requirements based on the criteria give by (Kano et al., 1994). An interactive approach is proposed to collect and prioritise customer requirements. Marketing people first collect customer requirements through market research. Marketing, Development and customers conduct trade-off analysis among these requirements jointly. By doing so, it is possible to predict potential Phase 1 reliability problems. Next this method performs a diversity analysis (Mil et al., 1994) to identify the relation between prioritised customer requirements and production process steps and product parts. Such relation indicates whether it is necessary to introduce changes in product parts and production processes in order to fulfil customer requirements. When it is necessary to introduce some incremental changes, it is suggested to perform computer simulations, real experiments or robust design to introduce these changes so that the probability of occurrence of associated potential reliability problems can be predicted and reduced.

5.3.2. Process related Requirements

Managing uncertainty in a CFPDP

This requirement is not related to the detailed design of RQM but related to the way that this method should be used in a CFPDP. As discussed already, the diversity analysis in RQM can help in making decisions on what changes need to be introduced to existing products and production processes so as to meet customer requirements. In other words, this method is able to determine what product parts and production process steps can be taken directly from existing products and production processes and what has to be changed. By further identifying the potential reliability problems associated to these parts and process steps, RQM can be applied to select and evaluate a product concept. Therefore it is proposed that this method be used first very early in the PDP, preferably before choosing the product concept. Already from that milestone, the possible uncertainty in reliability prediction can be identified. When the PDP progresses, this method should be updated regularly based on more valid product information from reliability related activities, e.g. reliability tests. When customer information, field information and production information are available, the output of the method can be also evaluated. All CFPDPs in parallel can exchange useful information through RQM so as to prevent the reoccurrence of same reliability problems. By doing so, the status of uncertainty in reliability prediction can be monitored as a function of time and the PDP managers can be always aware of whether the degree of uncertainty decreases in the PDP and how it decreases over time.

Table 5.1 Different ways of handling uncertainty by RQM and FMEA

Reliability problem prediction and prevention		RQM		FMEA	
Potential reliability problem		Reducing uncertainty	Reducing probability of occurrence	Reducing uncertainty	Reducing probability of occurrence
Uncertainty level	Probability of occurrence				
Rough estimate	High	1	2*	-	1
Rough estimate	Low	1	2*	-	-
Model-based estimate	High	1	2*	-	1
Model-based estimate	Low	1	2*	-	-
Validated estimate	High	-	1	-	1
Validated estimate	Low	-	-	-	-

1, 2: The sequence of uncertainty reduction activity and probability of occurrence reduction activity

*: Activity will take place when necessary (only if the probability of occurrence level is still high after uncertainty reduction)

-: No action takes place

5.4. Models/Concepts used in the design of RQM

The objective of developing RQM is to proactively prevent potential reliability problems, especially those previously unpredicted Phase 1 reliability problems, already early in a CFPDP including the aspects of uncertainty. Considering the three different phases in a CFPDP based on the PDP definition used in Chapter 2 (PDMA, 2001; Clausing, 1994), Concept development, Product design and Production[6], RQM should be therefore designed in a way that all the potential reliability problems related to all these phase can be identified and prevented including the aspects of uncertainty. As discussed in Chapter 2, (Phase 1) product reliability also depends on how customers use the product. In a business-to-business CFPDP, customer requirements, to a large extent, determine how customers use the product, which is not the case for a business-to-end user CFPDP. Therefore, RQM should be also able to prevent potential reliability problems related to customer requirements. As a result, a 7-step process is developed and it is named as RQM. Table 5.2 describes its structure.

Table 5.2 The process of RQM

Steps in RQM	Description
Step 1	Prioritise the customer requirements
Step 2	Customer requirement trade-off analysis
Step 3	Identify the production process steps and product parts
Step 4	Identify the relation between prioritised customer requirements and process steps or product parts; indicate known or unknown status for product process steps or product parts
Step 5	Identify potential product and production process related reliability problems
Step 6	Predict failure probability of the potential reliability problems related to both known and unknown production process steps and product parts
Step 7	Predict reliability performance in the factory and at customer sites

Obviously, the RQM process is closely related to a CFPDP.

♦ All 7 steps together are designed to prevent potential Phase 1 reliability problems due to customer use and all the three phases of a CFPDP including the aspects of uncertainty. Steps 1 and 2 are designed to prevent potential Phase 1 reliability problems due to customer use, Steps 3 and 4 are designed to prevent potential Phase 1 reliability problems in the Concept development phase, Steps 5 and 6 are for the prevention of potential Phase 1 reliability problems in the Product design phase and Step 7 is to prevent potential Phase 1 reliability problems in the Production phase.

[6] These three phases are in parallel in a CFPDP.

♦ Same as the three phases in a CFPDP, all 7 steps are not necessarily to be performed in a sequential manner. For example, step 1 and 2 can be finalised after a few rounds of discussion.
♦ The RQM process is to be applied already before the Concept development phase. It is also to be updated before the Product design phase and the Production phase.

In conclusion, the 7-step in the RQM process follows the flow of a CFPDP (Figure 5.2).

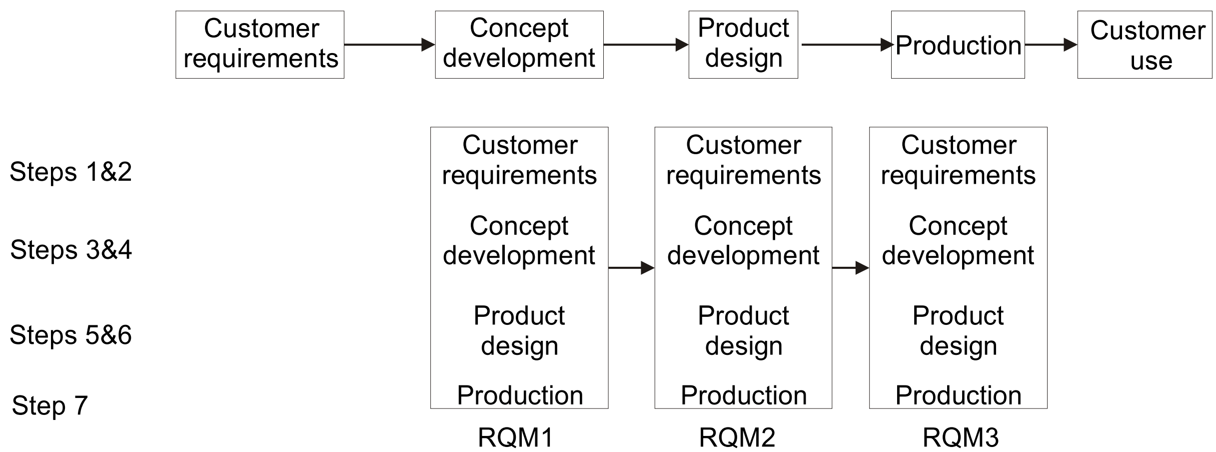

Figure 5.2 RQM and its relation with a CFPDP

By applying RQM already at the Concept development phase and updating it also during the Product design phase and the Production phase, it is possible to monitor how uncertainty is managed in a CFPDP (Figure 5.4).

In order to structure the data collected from RQM, an Excel-based spreadsheet (Figure 5.3) is also developed. The next part of this section discusses each step in more detail.

Step 1. Prioritise the customer requirements

This step is very important for managing customer use related Phase 1 reliability problems in CFPDPs. By promoting the thorough understanding of the customer requirements, the likelihood of having those Phase 1 reliability problems can be reduced.

Based on customer's preferences and extensive market research, customer requirements are to be prioritised first. These requirements can be prioritised into three major categories, the Must, the Linear satisfier and the Nice-to-have. These three categories of customer requirements are explained in detail below.

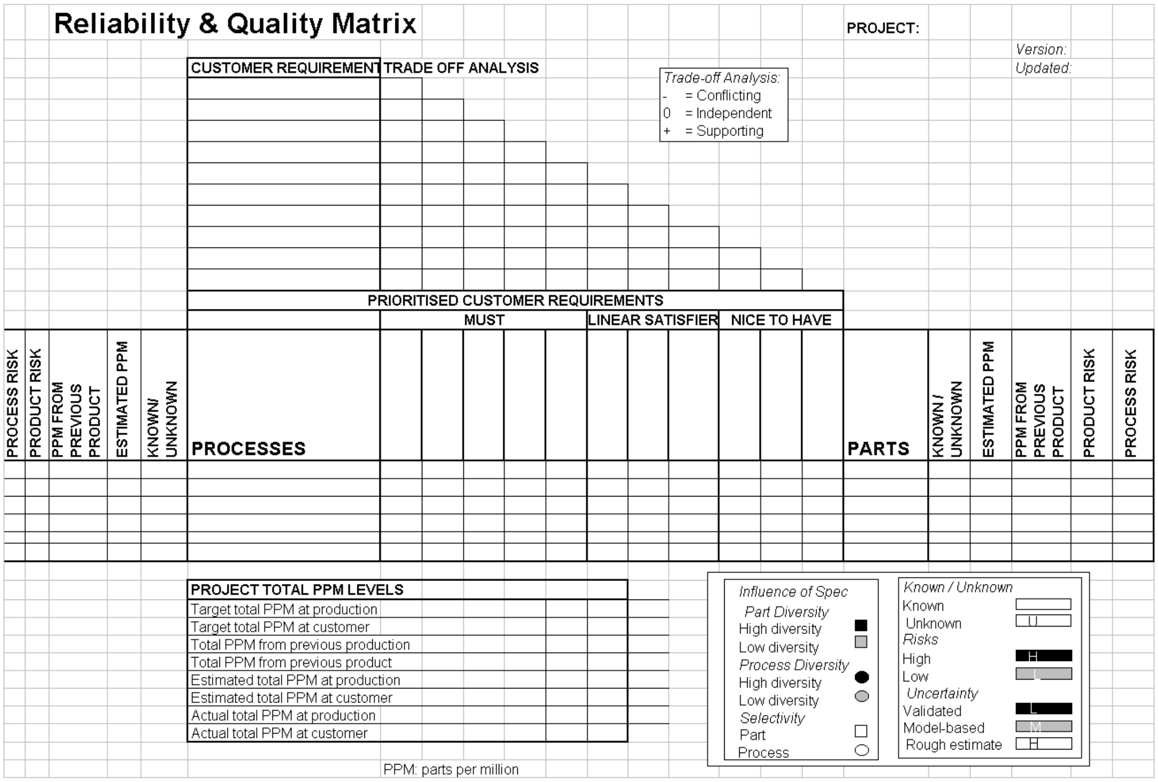

Figure 5.3 A prototype of RQM – an Excel-based spreadsheet

Must requirements refer to those requirements (Kano et al., 1994) that customers simply expect in the product. However, the customers are not motivated to buy the product because of those requirements only, but if they are lacking in the product then customers will be extremely dissatisfied. Linear satisfier requirements refer to those one-dimensional requirements (Kano et al., 1994) that have a linear satisfying effect on the customers. The more these requirements are fulfilled, the more the satisfaction for the customers. The less these requirements are fulfilled, the less the satisfaction. Nice-to-have requirements refer to those exciting requirements (Kano et al., 1994) that customers do not expect. They can create an excitement for the product. However, even if they are not there it has no effect, as customers do not expect them in the first place. The relation among these three different types of customer requirements is shown in Figure 5.5 (Kano et al., 1994). The vertical axis represents the level of customer satisfaction from low to high while the horizontal axis represents the extent to which customer requirements are met or not met. The arrow that represents Must requirements (a) shows that if customer needs are not met the customer is unhappy; if the needs are met it is not a big deal to customers. The arrow that represents Linear satisfier requirements (b) shows that if they are fulfilled customers are satisfied; if they are not fulfilled customers are dissatisfied. The arrow that represents Nice-to-have requirements (c) shows that if a product is developed with a very good new feature that surpasses customers expectations, then may be excited and delighted. The Kano three-arrow model has also been used to develop other methods, such as QFD (Akao, 1990).

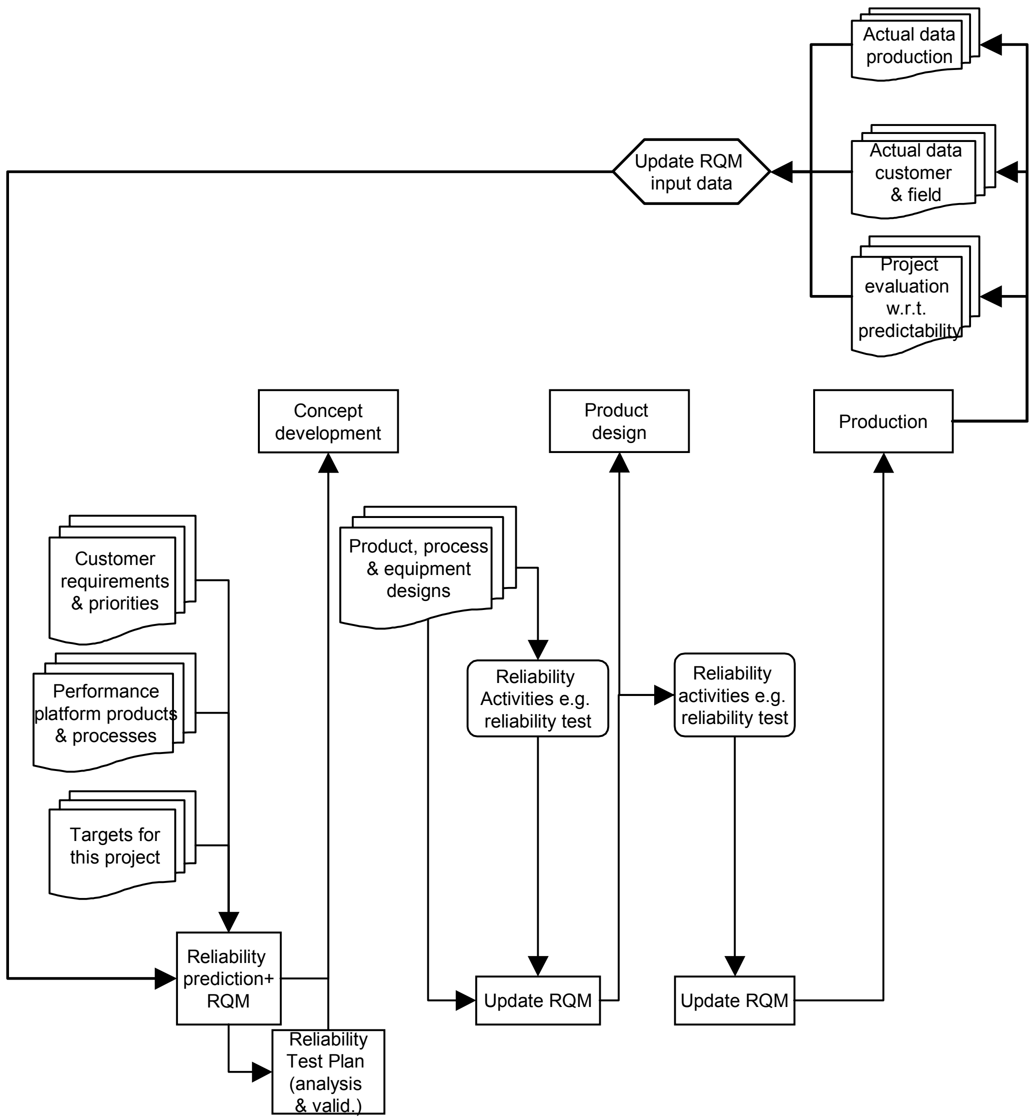

Figure 5.4 Integrating RQM in a CFPDP

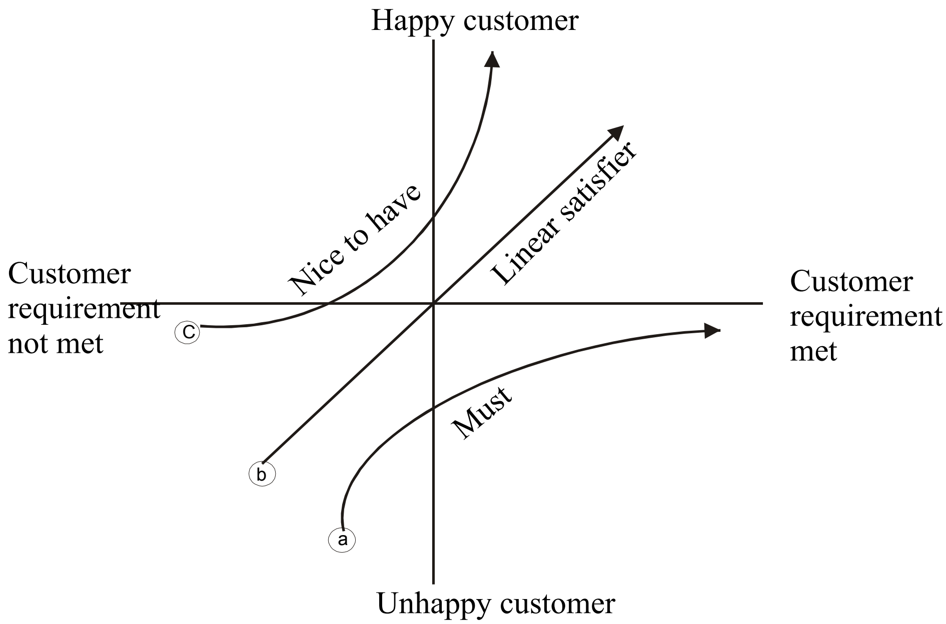

Figure 5.5 Kano three-arrow model (Kano et al., 1994)

The selling points of derivative products, most of time, fall into satisfying Nice-to-have requirements or Linear satisfier requirements because Must requirements only guarantee the derivative products would perform more or less as the platform products. For example, after the introduction of an expensive CD-player in the market, a derivative version is developed with the same functionality but at a cheaper price, customers would be excited and delighted to buy this new version, not because it is a CD-player but because it is a cheaper CD-player. Another example, which can give, is about the mechanical noise level of a family Hi-Fi set. Customers would be happier if the mechanical noise level is lower and they would be less satisfied if the mechanical noise level is higher. If a derivative family Hi-Fi set has an enhanced performance against mechanical noise, customers would be more willingly to buy this product. Therefore, identifying these three kinds of customer requirements is the most important initial step in the proposed reliability method. It provides the overall scope that potential reliability problems may arise from. They should be agreeable to the customer and also well understood throughout the project team. For example, key members from the Development Department and the Quality Department can visit the customer together with Marketing people to have a first-hand view of the requirements of the customer. It should be followed by a detailed discussion on the technical feasibility of fulfilling the requirements. If some features are Must from customer requirements, then it is for sure that technical capability to satisfy them must be built up. If the selling points are related to some Linear satisfier requirements or some Nice-to-have requirements and it is not sure whether they can be met, earlier decisions are strongly recommended to regard them as potential reliability problems and derive effective and efficient handling plans for them. Those requirements, which are not Must requirements and have very limited connection to the selling points, can be considered only when they become more interesting than the three major customer requirements. By doing so, only the most important customer requirements are considered and project development efforts are well focused under TTM pressure.

Step 2. Customer requirement trade-off analysis

The first step of the RQM process is often organised by the Marketing Department. It is highly possible that the prioritised customer requirements are not completely independent from a technical point of view. If only the prioritised customer requirements from Step 1 are considered, it is possible that some critical customer requirements will not be satisfied. The likelihood of having customer use related Phase 1 reliability problems is then high. Under this circumstance, the voices from development departments involved in the project team are also necessary. Therefore, during the Step 2, it is expected that the project team to discuss the trade-offs relation among different customer requirements based on experiences from the existing products.

During the trade-off analysis, three types of relations among the customer requirements can be distinguished:

♦ Conflicting requirements. They are those requirements that conflict with each other, i.e., an improvement in one can lead to the degradation of the other. For instance, speed and play noise are conflicting requirements for a CD-Player. Faster speed invariably creates more play noise.
♦ Independent requirements. They are those requirements that have no relation with other requirements. For example, “Reading non-finalized disks” is an independent requirement for a CD-player. It does not affect other customer requirements. Thus increasing or decreasing their performance has no effect on other requirements.
♦ Supporting requirements. They are those requirements that support other requirements. An improvement in one leads to an improvement of the other. An example of supporting requirements is lower power consumption leads to more tolerance of the ambience temperature due to reduced heating of the CD-player.

After that, the customer requirements should be re-prioritised. On the basis of these trade-off results, if necessary, further re-negotiation with the customers should be considered. The analysis results will be fed back to Step 1 to further prioritise the customer requirements in Step 1. Obviously, Step 1 and Step 2 are inter-linked and hence they can be finalized after a few rounds of discussions.

For example, cost requirement and the play noise requirement are both considered as Linear satisfier for a CD player during Step 1. After the trade-off analysis, they are considered as conflicting requirements because the price of the product to a large extent also determines the quality of the product. Further discussion with the customers reveals that the cost requirement is the most important one compared with the play noise requirements. It is decided later that the cost requirement will be still considered as a Linear satisfier while the play noise requirement will be move to the category Nice-to-have and will be only taken into consideration when condition allows (e.g., there is still enough project budget under the cost requirement).

Step 3. Identify production process steps and product parts

Step 4. Identify the relation between prioritised customer requirements and product process steps or product parts; indicate known or unknown status for product process steps or product parts

Steps 3 and 4 are designed to prevent potential Phase 1 reliability problems in the Concept development phase. In CFPDPs, mature building blocks are quickly integrated by using proven technologies. In their Concept development phase, the building blocks (product parts) as well as the integration process steps (production process steps) are to be determined. Therefore, in these twp steps, it is expected to first identify the necessary product parts (building blocks) and production process steps (integration process), and the relation between them and the prioritised customer requirements. By analysing such relation it is possible to identify the potential Phase 1 reliability problems in relation with the concept development.

In Step 3, product parts (building blocks) and production process steps (integration process) are to be identified. In order to do so, the complete parts list and production process flow for designing and producing the product are to be identified. For the process flowchart all the detailed production steps are to be mentioned separately. This means that even if multiple parts are assembled on one workstation, they will still appear as separate steps. Since this is a derivative product, the production process flow and parts list of the platform product is known and can be copied first.

In Step 4, a diversity analysis is performed to identify the relation between the prioritised customer requirements and the parts list and process steps. High diversity and low diversity are used to distinguish the level of relation. Three levels of relations are used to show the impact of prioritised customer requirements on product parts and production process steps. They are part diversity, process diversity, and no relation. They also indicate on the known or unknown statuses of the production process steps and product parts, depending on whether the changes required are known or unknown to the company.

- Part diversity is used to indicate when a part needs to be redesigned to fulfil a customer requirement. When a customer requirement causes a part to be changed, and therefore to be redesigned, this is called "high diversity". It is more likely to have Phase 1 reliability problems reported by the customers. An example is that the turntable motor is changed to a brush-less motor to satisfy the speed requirement of a CD module. Phase 1 reliability problems may occur when the change of the turntable motor causes unsatisfactory of the speed requirement. When a customer requirement causes a part to be changed, but this only leads to minor modifications (keeping the same references / tolerances / material / interfaces) this is called "low diversity". It is less likely to have Phase 1 reliability problems reported by the customers. An example is that the spring wire is changed to satisfy the speed requirements in a CD module.
- Process Diversity is used to indicate when a process has to be changed to fulfil a customer requirement. When a customer requirement causes a process to be changed, and therefore induces a major change over in the factory, this is called "high diversity". When a customer requirement causes a process to be changed, and therefore induces a minor change over in the factory (same machine, same production targets, only easy change in settings (software)), this is called "low diversity"
- No relation is used to indicate when there is no relation between the customer requirement and the process or part. For example, customer requirement for shock sensitivity has no relation to the sledge motor in a CD module.

Based on the changes that need to be introduced to product parts and production process steps, it is also possible to indicate their known or unknown statuses. Unknown product parts or production process steps are those with changes that have not been used before in the company in a similar application, while known parts or production process steps are those with changes that have been used before in the company in a similar application.

Step 5. Identify potential product and production process related reliability problems

Step 6. Predict failure probability of the potential reliability problems related to both known and unknown production process steps and product parts

Steps 5 and 6 are designed to prevent potential Phase 1 reliability problems in the Product design phase. In Step 5, potential reliability problems are identified qualitatively. Brainstorming sessions are conducted to identify potential product and production process related reliability problems based on experiences from knowledge from the existing products.

- Production process related reliability problems. Two types of production process related reliability problems are to be identified. A process-to-process reliability problem refers to the situation when a process step is difficult to implement and it affects the production targets. A process-to-product reliability problem refers to a product failure caused by a problem in a process step.
- Product related reliability problems. Two types of product related reliability problems are to be identified. A part-to-process reliability problem refers to a production process failure caused by a particular component. A part-to-product reliability problem refers to a product failure caused by a particular component.

The impact of the reliability problems with relation to the product and production process is qualitatively indicated with high severity, low severity or no severity. High severity refers to the severe impact that may be caused and low severity refers to the minor impact that may be caused. If there is no impact, then it is indicated as no severity.

In Step 6, the quantitative information, the probability of occurrence (failure probability) of the potential reliability problems related to each process step and product part, is generated with reflection on its uncertainty level due to the uncertain reliability information used. Three uncertainty levels are used to reflect the uncertainty involved in the prediction/estimation. Table 5.3 indicates what kind of information can be used to estimate the probability of occurrence and what is the associated uncertainty level.

Table 5.3 Estimating the probability of occurrence of the potential reliability problems

Status of product parts and process steps	Different sources of information			
	Information from previous products and production processes or trial run		Information from computer simulation or real experiments	Information from rule of thumb
	Reliable	Unreliable		
Known	Validated estimate	Rough estimate	Model-based estimate	-
Unknown	-	-	Model-based estimate	Rough estimate

It is recommended in this step that

- Probabilities of occurrence for known process steps and parts should be directly copied from the platform product if the technical capability remains the same and the information used from the platform product has a good quality level. Their uncertainty levels are considered the same as “Validated estimate”. If the information is not as good as expected for some known process steps or product parts, they become unknown immediately. If the project team still decides to use this information, these estimates have to be considered as “Rough estimate”.

♦ For unknown processes and parts, early robust design analysis, computer simulation, or even practical tests on their tolerances and interactions with the known process steps and product parts can be done to estimate their contributions in the final production performance. Then their uncertainty levels are considered the same as “Model based estimate”.

In the Excel spreadsheet, three different background colours are used to indicate the uncertainty level of the correspondent predictions. They are light blue, middle blue and dark blue. If the probability of occurrence is roughly estimated without reference from the platform product or from any computer or real experiment, a high uncertainty level is assigned to this estimation result and this estimation is called as a “Rough estimate” and the background colour of the corresponding cell in RQM is filled with light blue. By doing so, NP, PPP and RMP are immediately be marked with light blue in RQM and they all expect further action. If the probability of occurrence is estimated with reference through computer simulation or real life experiment, a medium uncertainty level is assigned to this estimation result and this estimation is called as a “Model based estimate” and the background colour of the corresponding cell in RQM is filled with middle blue. Introducing such a step can help monitoring the progress of reducing uncertainty in reliability prediction. If solid evidence from the platform product or trial run is used to estimate the probability of occurrence, a low uncertainty level is assigned to this estimation result and this estimation is called “Validated estimate”. The background colour of the corresponding cell in RQM is filled with dark blue. Having a few dark blues in RQM indicates that they are real problems and actions have to be taken to reduce the problem with the highest probability of occurrence.

Step 7. Predict reliability in production and at customer site

Step 7 is designed to prevent potential Phase 1 reliability problems in the Production phase. Based on the predicted contribution of each process step and product part, product reliability in production can be predicted. If the test efficiency at customer sites is known as well as the reliability of the transportation between a company and its customer is known, product reliability reported by customers can be predicted as well. Depending on the uncertainty level of the individual prediction for the process steps or product parts, the uncertainty level of these two predictions is determined. If one individual prediction is from a “Rough estimate”, then these predictions are also from a “Rough estimate”. If some of the estimations are from “Model-based estimates” and the others are from “Validated estimates”, these predictions are from “Model-based estimate”. Only when all the individual predictions are from “Validated estimates”, these predictions are from “Validated estimates”.

5.5. RQM and QFD

Step 1 and 2 of the RQM process is very similar to some elements in a QFD analysis as they are all based on the Kano three-arrow model (Kano et al., 1994). In fact, QFD and RQM have a lot of things in common. They can be both used to prevent potential quality and reliability problems. Both require a thorough understanding of customer requirements. QFD tends to bridge the gap between customer requirements and technical specifications. RQM tends to manage potential reliability problems that may not satisfy the prioritised customer requirements including the aspects of uncertainty.

In general, QFD can give RQM good input about customer requirements, RQM can feedback to QFD whether the customer requirements can be fulfilled. They are both very applicable to concurrent PDPs.

Although they have many things in common, they are still different. For example, QFD can be applied to both radical PDPs as well as derivative PDPs, while first developed RQM is to be applied in derivative PDPs. The major difference lies in the way that uncertainty is managed in using the two methods. As discussed earlier, RQM tries to prioritise uncertainty reduction activities when managing reliability, but in a qualitatively manner. Schmidt (Schmidt, 1997) highlighted the fact that during the implementation of QFD, people need to determine the quantitative relation between customers’ needs and design characteristics and quite often neglect the high degree of uncertainty that they may have to face (European Journal of Operations Research) but traditional QFD and QFD practice often ignore this fact. To deal with this uncertainty, recent development in QFD suggests the use of “fuzzy QFD” (by using membership function) (Schmidt, 1997). But how it works in real life is not explicitly discussed. To apply the same concept (using membership function) in RQM to quantitatively describe the uncertainty in reliability prediction is at the moment not possible. This is because it is not yet possible to quantify the relation between the quality and the use of the information and the predictability of potential reliability problems. Therefore RQM is designed in such a way that uncertainty in reliability prediction is qualitatively managed in CFPDPs.

5.6. RQM and FMEA

In terms of functionality, RQM and FMEA are very close to each other. They both can be applied to identify potential reliability problems in a systematic manner. As discussed already in previous Chapter, FMEA is not able to prevent the process-flaw related Phase 1 reliability problems in CFPDPs when using uncertain information. That was the motivation of the development of RQM. When managing potential reliability problems, RQM is designed so that uncertainty reduction activities are always prioritised over failure probability reduction activities while FMEA focuses mainly on failure probability reduction activities. The major impact of using RQM in CFPDPs is that uncertainty reduction related development activities are prioritised over failure probability reduction activities compared with classical CFPDPs.

Figure 5.6 and Figure 5.7 show the different ways of handling reliability problems by this method and by FMEA. When a reliability problem is predicted with a high probability of occurrence and a high degree of uncertainty, RQM tries first to reduce the degree of uncertainty involved in the prediction and then take further action to reduce the probability of occurrence if necessary (curve 1 or 2 in Figure 5.6). By doing so, the problem can be reduced to a problem with low probability of occurrence and low degree of uncertainty. Under the same circumstance, FMEA immediately tries to reduce the probability of occurrence without considering the uncertainty involved in the prediction. In most cases, it stops when the probability of occurrence seems to be reduced (curve 3 in Figure 5.6). This problem can become one of the NP, PMP and PPP later or even be reported by customers an unpredicted reliability problem. When a reliability problem is predicted with a low probability of occurrence and a high degree of uncertainty, RQM still tries first to reduce the degree of uncertainty involved in the prediction and then take further action to reduce the probability of occurrence if necessary (curve 1 or 2 in Figure 5.7). By doing so, the problem can be reduced to a problem with low probability of occurrence and low degree of uncertainty. Under the same circumstance, FMEA simply overlooks this reliability problem due to the predicted low probability of occurrence (curve 3 in Figure 5.7). However, this problem can become one of the NP, PMP or PPP later in the process or even be reported by customers as an unpredicted reliability problem.

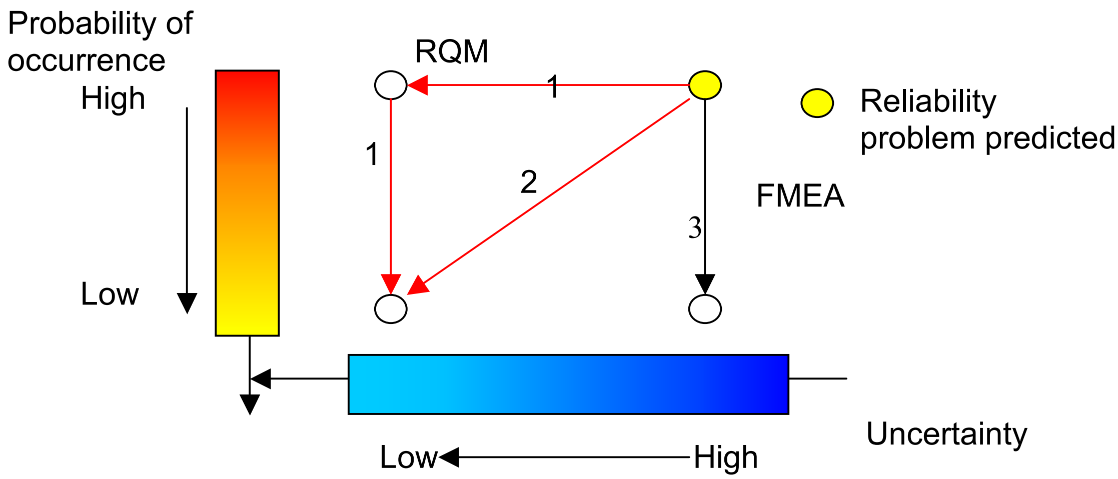

Figure 5.6 Managing reliability problems with uncertainty I

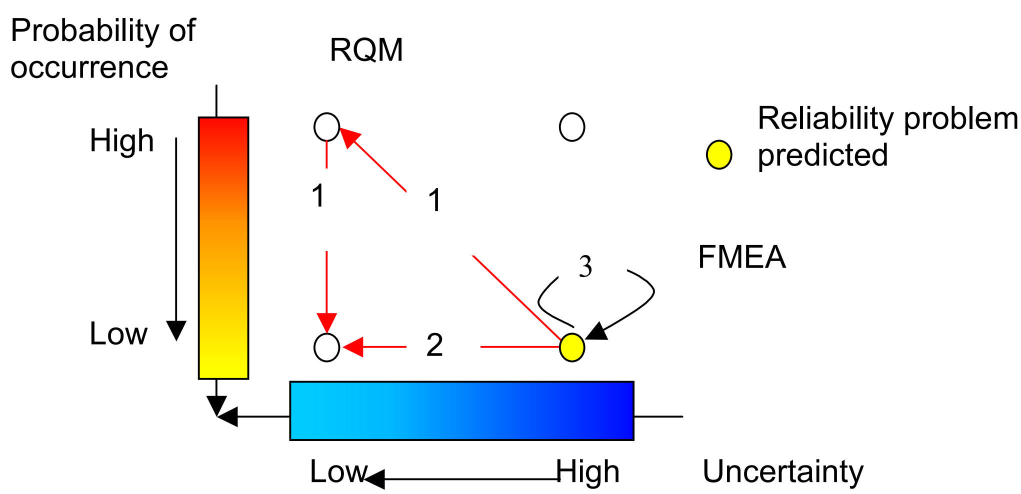

Figure 5.7 Managing reliability problems with uncertainty II

5.7. Conclusion

In this chapter, a reliability method, RQM, is developed to predict and prevent potential reliability problems using uncertain information in CFPDPs. The formal requirements of such development as well as the structure of this method have been addressed here. From a method point of view, being able to classify, prioritise and monitoring uncertainty in reliability prediction RQM enables effective prediction, reduction and management of unpredicted reliability problems. By analysing customer requirements and their relation to product parts and integration processes, RQM also enables the improvement of Phase 1 reliability problems. From a process point of view, RQM can be implemented in the very early stage of the PDP. Potential reliability problems can be identified proactively and correctly when highly uncertain reliability information is involved in the prediction. Necessary early design changes, and reliability test plans can be derived to prevent or resolve these problems accordingly. RQM can be updated continuously based on the results of the reliability tests during the PDP. Therefore, it can be concluded that RQM is able to classify and prioritise the uncertainty involved in the reliability prediction in time; it reduces the uncertainty before the probability of occurrence; it continuously monitors the uncertainty during reliability prediction along the PDP.

RQM is, to a large extent, very similar to FMEA and QFD. However, QFD and FMEA often neglect the fact that the input information may be somewhat uncertain. The developed RQM takes a different attitude towards uncertainty management. It promotes the proactive management of uncertainty in CFPDPs. By using RQM, uncertainty reduction related development activities are prioritised in these PDPs.

The development of RQM and the structure of the method are discussed above. However, any good reliability methods, tools, concepts and strategies can be only effective if they are successfully implemented. In the next Chapter, a real life implementation case will be presented.

CHAPTER 6 IMPLEMENTING AND EVALUATING RQM IN AN INDUSTRIAL CASE

6.1. Introduction

This chapter presents the implementation of RQM in an actual, industrial, environment. It describes the design of the field experiment, the actual implementation process and the evaluation of the results achieved. It also discusses the applicability of RQM in another industry and non-derivative PDPs.

In Section 6.2, a few criteria are discussed to select an industrial case to implement RQM. This case is described in Section 6.3. After that Section 6.4 gives a proposal to implement RQM in the PDP. The detailed execution is discussed in Section 6.5. Implementation results are discussed in Section 6.6. Reflection on the implementation results is given in Section 6.7. RQM is further refined in Section 6.8. Section 6.9 also discusses the applicability of RQM in other industry and non-derivative PDPs. Conclusions are given in Section 6.10.

6.2. Case Selection

Chapter 5 of this thesis has shown that, in certain CFPDPs, the uncertainty of information is one of the main causes of the inability of the PDPs to achieve predictable reliability (many unpredicted Phase 1 reliability problems). In order to solve this problem, a tool was designed to predict reliability problems when using uncertain information during such PDPs. It was expected that by using this tool, Phase 1 reliability problems could be prevented there. Although the applicability of the tool should be much wider than a single product in a single company, it was necessary to prevent, as much as possible, the influence of unpredicted disturbing factors. Therefore, the tool was tested on a similar product within the same company as where the original research was carried-out. In principle, a suitable project that can be used to test the tool should be very similar to the previous project, where the research problem was identified, from the product point of view as well as from the PDP point of view. As a result, the following criteria should be fulfilled:

- The product has to be very similar to the product that was studied before in the earlier case studies and it should fulfil the same requirements
- The structure of the PDP that develops the product should be the same as the old PDP
- The project team which develops the product should be largely the same
- The owner of the PDP should allow RQM to be implemented during the entire PDP

When these requirements are fulfilled, it is possible to evaluate the tool.

6.3. Case Description

The product is a derivative product from the product studied in the earlier case. The two products are almost identical except for one small change to reduce the product cost. In some areas, this product used some cheaper components while the old product used more expensive ones. The new components had been used before in other products. As soon as this product was released, it would replace the old one in the market. With such changes, no specification changes were required from the previous product. The same PDP structure that was described in Chapter 3 was applied to develop this product and the same project team that developed the old product also developed this product. It was also learnt that by the time it was proposed to implement the method in the company, this PDP had just started. Using the selection criteria, mentioned earlier, this project was therefore an ideal candidate for implementing RQM.

6.4. Implementation Strategy

Based on the developed method, RQM should be used first before the CS milestone. According to the old PDP structure, FMEA and reliability tests were the main instruments to manage reliability problems in the PDP. Since these tools were unable to handle uncertain information, RQM was designed to manage especially uncertain information related to product parts and production process steps. It prioritises uncertainty reduction over “probability of occurrence” reduction. Once the uncertainty level of information with respect to a potential reliability problem is reduced, it streamlines action plans to reduce the probability of occurrence in a manner similar to FMEA. In order to avoid too much overlap between the (new) RQM activities and the (existing) FMEA activities, uncertainty reduction was performed via RQM, while managing the subsequent actions was performed via a series of subsequent FMEAs. In order to verify the resulting corrective actions, reliability tests were implemented. In process terms, this means that RQM is used as input for FMEAs and reliability tests. The results of FMEA and reliability tests are also used to update RQM. In this manner the related uncertainty in reliability prediction can be also updated. In order to fit within the existing PDP framework, it was suggested to update the results of RQM before AFM, CMD, DR and IR milestone. In case the designed system would work correctly at the DR milestone, most of the uncertainty in reliability prediction should have been reduced, and most of the predicted reliability problems should have been managed accordingly.

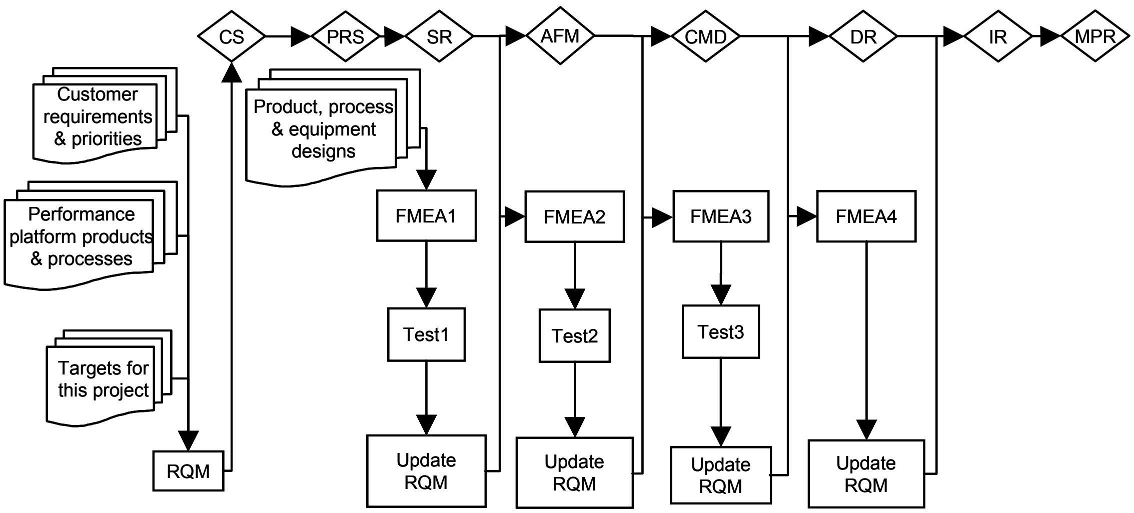

Figure 6.1 Proposal for implementation of RQM in the PDP

It was decided that RQM would be starting with a briefing session for the relevant project team members. The participants were required to prepare the required input information (including information required to determine the uncertainty level) before the meeting. During the session the gathered information was put into the RQM tool. In order to prevent (unintended/undesired) influence of the researchers on the project, it was decided that a representative from the company would be selected to facilitate the session and update the spreadsheet during the session.

6.5. Operating RQM during the PDP

It was not possible to implement RQM five times in the PDP as planned due to unplanned changes in the project team (changing project manager) in combination with a very tight development schedule. It was decided that three RQM sessions would be implemented. In this first project[7], one session was performed before the CS milestone and the other two were performed before the CMD and DR milestone.

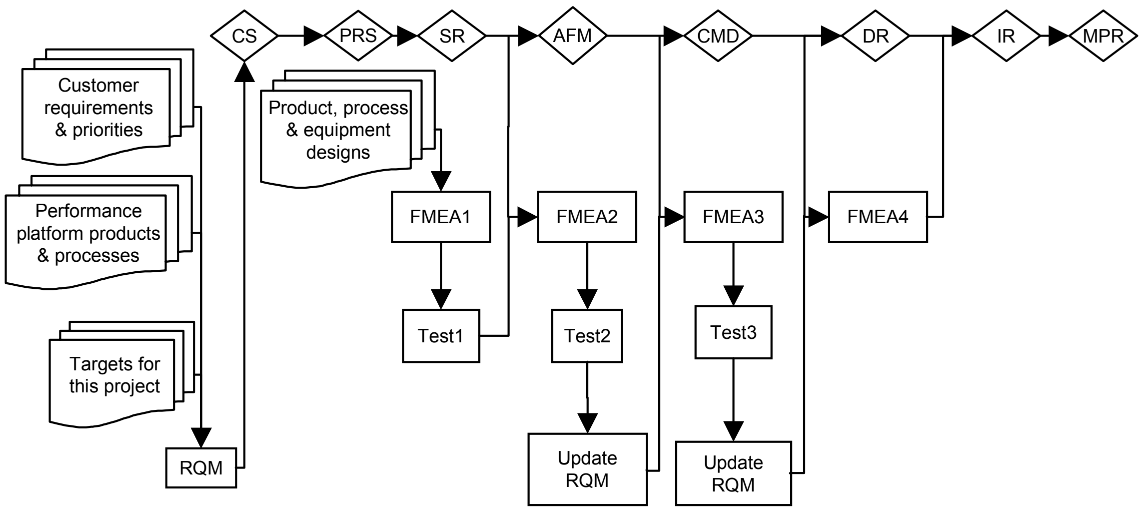

Figure 6.2 Actual implementation of RQM in the PDP

A person from the Quality Assurance Department who was not involved in the product was appointed to facilitate RQM sessions. The researchers helped this person to get familiar with the method before the implementation. The first RQM implementation took an entire day. Other than explaining the tool, the researchers performed only the role of observers. The results were used to fill up the Excel-based spreadsheet and presented in the CS milestone meeting. RQM was then updated two times before the CMD and DR milestone. These two sessions were organised by the company alone without external parties present. Each session took about half a day. Detailed implementation results are discussed in the following section.

6.6. Implementation Results

During the pilot project, the 7 steps were followed. The results are discussed below.

Step 1&2: Prioritise customer requirements and customer requirements trade-off analysis

Since the product is very similar to the previous product, its customer requirements were also the same. Initially the project team considered all the customer requirements Must

[7] In later projects the full sequence of RQMs was executed

requirements. Considering the fact that all the customer requirements were “Musts”, a trade-off analysis among the customer requirements was not possible. This gave the project team very little flexibility to allocate project resources and plan project activities to meet all the requirements. Therefore, discussions among Project Management, Marketing Department, and Development Department were held to re-prioritise those customer requirements. The customer was also invited in the discussion when necessary. For example, the requirement of the speed of the product and the requirement of the play noise of the product were both initially considered as “Must” requirements. During the re-prioritisation session, development people highlighted the fact that these two requirements are actually conflicting requirements: the faster the product is the noisier it is. During the following up discussion with the customer, it was learnt that the requirement on the play noise of the product was more important and the requirement on the speed of the product was “Nice-to-have” for the customer. Therefore, the noise requirement was considered as a “Must” requirement and the speed requirement was considered as a “Nice-to-have”. Related development activities were then mainly focused on how to satisfy the play noise requirement. If the development budget (time, cost and resources) allowed, the technical solution to fulfil the speed requirement would be also considered without dissatisfying the play noise requirement.

Step3&4: Identify the production process steps and product parts; correlate them with customer requirements and indicate known and unknown process steps and product parts

After the customer requirements were prioritised, the necessary production process steps and product parts were identified. Product parts and production process steps were firstly directly copied from previous products. The customer requirements were correlated to the process/parts. The only changes in this product were that some components were changed for cost reduction purposes. As a result, the related production process steps had to be changed, for example, the grating adjustment process was one of them. Although the company applied these changes before in other products, the team was aware of uncertainty in the information. Thus, it was decided that these changes would be considered as unknown. The unknown status suggested the team that the related prediction would have a highly uncertain level and necessary development activities would have to be planned in order to reduce the uncertainty level.

Step 5&6: Identify potential product and process related reliability problems; Predict failure probability for both known and unknown production process steps and product parts including the aspects of uncertainty

Four categories of potential reliability problems related to production process and product itself were identified.

♦ Process-to-Process risk – This is when there is a process that is difficult to implement. For instance, during the process “Insert PCB (Printed Circuit Board) on the LDGU (Laser Diode Grating Unit) leads” the leads have to be manually aligned and it could cause process problems.
♦ Process-to-Product risk – This is when there is a process that could cause product failures. For instance, although the grating adjustment is relatively simple, it is a major process-to-product risk as the adjustment leads to skewing of the LDGU.
♦ Part-to-Process risk – This is when a part causes problems in the process. For instance, LDGU could cause a lot of soldering & gluing process problems.
♦ Part-to-Product risk – This is when a part could cause product failures. For instance, the poor quality of LDGU could lead to product failures, such as laser dead, DC offset, etc.

The probabilities of occurrence of these reliability problems were also predicted. When the probabilities of occurrence of the reliability problems related to production process steps and product parts from the previous product were to be predicted, theoretically, they should be simply copied from the previous product and their backgrounds in the Excel-based spreadsheet were indicated with dark blue (validated estimate). However, due to the known uncertainty with the reliability information, the uncertainty levels of most of the predictions were defined as “Highly uncertain” and their background colours in the Excel-based spreadsheet were deliberately kept as light blue. For example, the use of a different LDGU implied that the grating adjustment process had to be changed. This business unit knew of such a change, but the related information was considered being uncertain by the project team. Thus, it was decided to adopt the probability of occurrence from previous production process and indicate the uncertainty level as highly uncertain.

Following uncertainty classification and based on the results of the diversity analysis, some robust design exercise (tolerance analysis) through computer simulation was immediately done to improve the uncertainty level of the earlier predictions. Consequently, their uncertainty levels were upgraded to medium uncertain and their backgrounds in the Excel-based spreadsheet were upgraded to middle blue colour. For the grating adjustment process, a robust design analysis was performed. The estimated probability of occurrence was used to replace the old prediction and the associated uncertainty level was set as medium uncertain.

Step 7: Predict reliability performance in the factory and at customer sites

Based on the early prediction made for production process steps, it was possible for the team to estimate the production yield with consideration of the associated uncertainty levels. Similarly, based on the early prediction made for product parts and the experience with customer way of testing, the team also predicted the potential product reliability that is to be reported by the customer.

In the end, all information was organized and filled in an Excel-based spreadsheet. Based on the results of the first RQM, a few real experiments were planned to reduce the uncertainty involved in the associated reliability prediction. Together with the results of FMEA2 and reliability test2, the team updated the results of RQM during the second session. The updated results were further presented in the CMD milestone. After FMEA3 and reliability test3, the team updated the results of RQM during the third session. These results were further presented in the DR milestone. An example of the resultant Excel-based spreadsheet is presented in the following figure. Because of the confidentiality agreement with the company, the fonts there are kept very small and detailed product related results would not be discussed here.

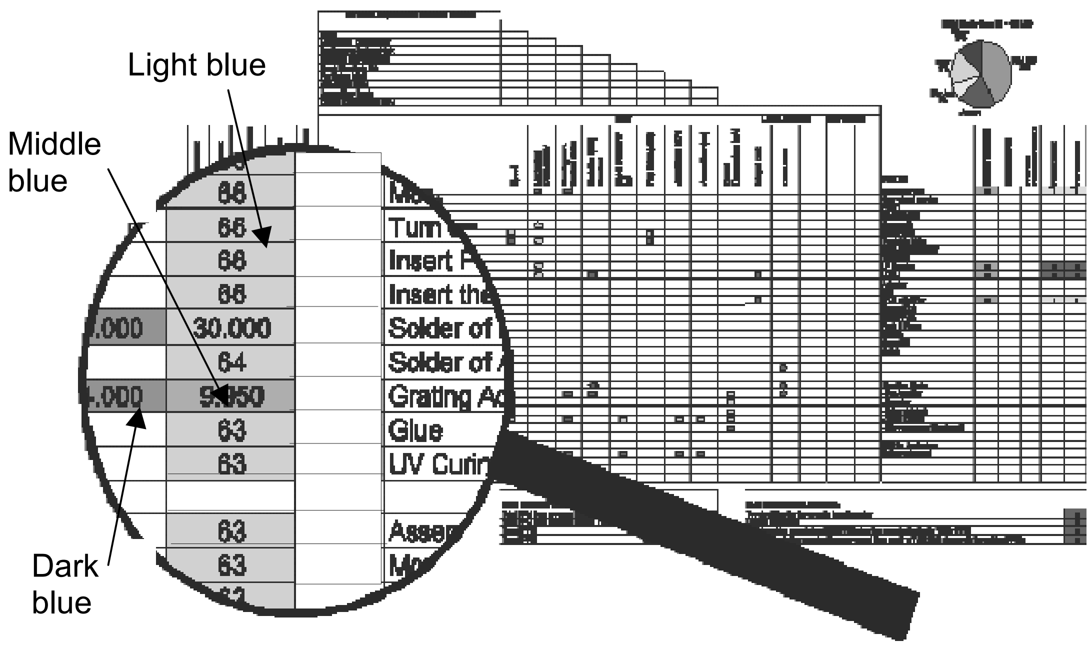

Figure 6.3 Results of RQM implementation at the CR milestone

6.7. Analysed Results

The objective of this research project is to develop a reliability prediction method so that unpredicted Phase 1 reliability problems can be prevented in CFPDPs. RQM is intended to classify uncertainty in reliability prediction, prioritise uncertain reduction activities, improve product reliability, and monitor uncertainty in the PDP as a function of time. By doing so, it is intended to anticipate and prevent Phase 1 reliability problems. It was known that five RQM sessions were planned and three of them were actually implemented in the process. A question naturally arises: can Phase 1 reliability problems still be anticipated and prevented by using RQM in this way?

The product that RQM was implemented for was based on the previous product studied in the case study discussed in Chapters 3 and 4. It was learnt that during the development of the previous product, most reliability problems were initially predicted as product-flaw related (some parts or components do not function as expected) when there was a high degree of uncertainty in reliability prediction. For example, the mechanical noise problem was initially predicted as being related to the reliability of a cheap mechanical motor, although it actually depended on the way that the product was tested, that is a process-flaw related problem. Since the degree of uncertainty in reliability prediction was overlooked, this problem was not identified by FMEA and reliability tests in the PDP. It was identified later by the customer as unpredicted Phase 1 problem. If applying RQM is not able to manage uncertainty in reliability prediction, it is most likely that the similar type of reliability problems would appear in the current product. Otherwise, this type of reliability problems should be prevented in the PDP.

According to the implementation results, two types of reliability problems could be distinguished.

- Reliability problems that were prevented in the PDP

  During the first implementation, the diversity analysis concluded that due to the use of a cheap component, Laser Diode Grating Unit (LDGU), a number of production process steps had to be changed, including the grating adjustment process and the soldering process. The team was not sure how these two changes would affect product reliability. From the experience in the development of the previous product, without including uncertainty in reliability prediction, the team would predict reliability problems as a function of the reliability of the components. The process-flaw related problems would not be predicted in the PDP but be detected by the customer as unpredicted Phase 1 reliability problems. By applying RQM, the team predicted these problems with a high degree of uncertainty and high probability of occurrence, and built robust design simulation models to reduce the uncertainty in these predictions. Reliability tests were performed later as well to update these predictions. The results of the following two RQM sessions clearly indicated that the uncertainty was gradually reduced and the related problems were step-by-step prevented in the PDP. Neither of them was reported by the customer. Based on the analysis, some general characteristics of these well-managed reliability problems in the PDP were observed. By using RQM, these problems were predicted with a high probability of occurrence and with a high degree of uncertainty. The team took immediately actions to first reduce the uncertainty involved in the prediction and then reduce the probability of occurrence. By doing so, uncertainty in these reliability predictions was managed and related Phase 1 reliability problems were prevented before reaching the customer.

- ♦ Reliability problems that were not prevented in the PDP

The results of RQM presented at the CS, CMD and DR milestone are summarised in Figure 6.4. It was observed that after the DR milestone there were still many reliability problems with high degree of uncertainty. Some of these problems were identified later by the customer. It was observed that the appearance of these problems was not because the company did not implement RQM as planned (three instead of five RQM sessions were conducted in the PDP) but because the way of handling uncertainty by the company needed to be improved. Two reasons were identified for causing these problems in the PDP.

- The team was more comfortable to work with certain reliability problems. It still had difficulties to handle uncertainty in reliability prediction with the help of RQM. Especially, when one highly uncertain problem was roughly estimated, the team always intended to assign a very low probability of occurrence to it (equivalent to Capability of Process Cp>=1.33) unless experiences showed that a high value was necessary. Thus, the team did not want to perform uncertainty reduction activity to this problem and hoped it would not become a real problem by the customer. However, the customer reported some of these problems. They are typical Phase 1 reliability problems due to mismatch between test specifications.
- The team tended not to distinguish between the degree of uncertainties related to the model-based estimate and the validated estimate. When a model-based estimate was generated based on computer simulations, experiments or robust design analysis, the team often considered it as a validated result if the estimated probability of occurrence was very low. However, due to using limited sample numbers as well as simplified models in these exercises, the uncertainty in model-based estimates cannot be overlooked and it is still necessary to start uncertainty reduction activities first. However, this was not done and in some cases, the customer reported some model-based estimates as real reliability problems. They are also Phase 1 reliability problems due to mismatch between test specifications.

It could be concluded from the case study that when the uncertainty in reliability prediction was well managed by using RQM, the related Phase 1 reliability problems were prevented; when it could not be managed by using RQM, it led to Phase 1 reliability problems reported by the customer. In addition, it could be also concluded that although RQM was not used as planned, it was already sufficient for the team to monitor the status of uncertainty management at the different moments in the PDP (Figure 6.4).

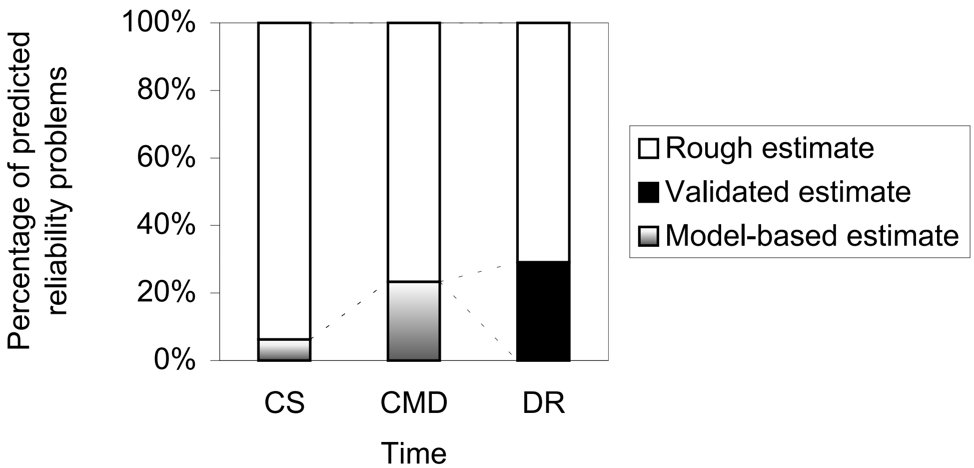

Figure 6.4 Managing uncertainty in the PDP

6.8. Refining RQM

It has been discussed in the previous section that by using RQM, the team was sometimes very successful in predicting and preventing unpredicted Phase 1 reliability problems and sometimes not. The main reason is that most of the time the team was still thinking in one dimension, reducing the probability of occurrence of a potential reliability problem, when managing reliability in the PDP through RQM was implemented. The uncertainty in reliability prediction was highlighted during the RQM session, but the decisions made to prevent reliability problems were based on the predicted probability of occurrence. If the predicted probability of occurrence of one reliability problem was high, actions were certainly taken to reduce the related uncertainty or to reduce the probability of occurrence. However, if it was low, there were no actions at all and the team simply hoped the related problems would disappear despite the presence of the associated high uncertainties. The researchers refined RQM so that by using RQM, the team could not neglect problems with high degree of uncertainty.

In order to make the effect of uncertainties more tangible for the team the process capability Cp was used, as this is a very common concept within the business unit. Cp is often used to indicate whether a process is under control (Bhote and Bhote, 2000). It is used here to refine RQM in order to better understand the uncertainty presented in rough estimate and model-based estimate. The following discussion should be considered as a practical guideline only.

When the degree of uncertainty in reliability prediction is very high, the output of the prediction can be unexpected, i.e., out of control. Therefore, it is suggested to use Cp=0.67 to roughly estimate the probability of occurrence as this value is often used to indicate that a process is out of control (Bhote and Bhote, 2000). By doing so, a rough estimate is always associated with a high probability of occurrence. As a result, the team has to take the associated problem more seriously and uncertainty reduction activities will be taken first. This will enhance the prioritisation of uncertainty improvement activities.

When computer simulations, real experiments, or robust design analyses are formed to estimate the probability of occurrence of a potential reliability problem, some times the estimated Cp can be higher than 10. Taking into account the uncertainty involved in these analyses, it is suggested to use Cp=1.33 to replace Cp>1.33 to estimate the probability of occurrence. This is because Cp=1.33 is often used to indicate that a process somewhat better under control, but it still needs to be improved (Bhote and Bhote, 2000). By using this value, the uncertainty related to model-based estimates can be highlighted.

6.9. Further Application of RQM

6.9.1. Applying RQM in the Business Unit

As the business unit was in the phase of finalising its formal procedure of a CFPDP, the management team approved RQM and it was officially included in the formal procedure. As a result, the business unit decided that all the future CFPDPs should use RQM as part of their processes. Now RQM has been applied in many CFPDPs in the business unit. By using RQM, it can manage uncertainty in reliability prediction in the PDP and predict and prevent Phase 1 reliability problems from happening at the customer site.

6.9.2. Applying RQM in a Company in the Domestic Appliances Industry

As mentioned earlier, RQM was developed for the fast development of derivative products in high-volume consumer electronics industry. A study was also conducted to investigate the feasibility of applying RQM in a company active in domestic appliances industry. The market that this company operates in has two characteristics: large variation in products and high speed to market. In short, customers are expecting a broad range of products in a short introduction window. Following this trend, the company has to include more special, high tech features to the products within a limited period of time. The question here is whether RQM can be applied in this company. The results of this study are presented below.

It has been discussed that RQM is suitable for a project that is associated with the fast development of a derivative product. Therefore, the products and the PDPs of this company were analysed. Besides producing highly innovative products to compete with competitors in the market, this company also developed many derivative products through practising the product development strategy of downgrading. It was learnt that based on the degree of technologies used, the products are divided into three groups: high-end products, medium-end products and low-end products. When a new product replaced an old product at the high-end level, this old product was modified, made cheaper, as a medium-end product; this modified product then also replaced the existing medium-end product and the old medium-end product would be modified further to replace the existing low-end product. As a result, this company has many ongoing derivative PDPs running in parallel. Concurrent engineering has been applied in these PDPs as well as to plan these PDPs in parallel.

Based on the discussion above, it can be concluded that RQM can be applied in this company. At this very moment, the first experimental application of RQM is taking place in the company. As the result of such experiment is out of the scope of this thesis, further results will not be discussed here.

6.9.3. Applying RQM in a Non-derivative PDP

As mentioned earlier, RQM was developed for the fast development of derivative products in high-volume consumer electronics industry. Effort has been also spent to implement RQM in the development of medical equipment used in hospitals. This product is a radical product in the professional product industry. It differs a lot from a derivative product in the consumer electronics industry. These differences had a major impact on the implementation of RQM. The kind of industry where RQM was developed manufactures high-volume consumer electronics products for the OEM market under strong TTM pressure. The correspondent strategy chosen by those companies is to develop many derivative products as fast as possible. The degree of innovation there is very low and products are mass-produced. The medical product, which was chosen for this study, is a highly innovative product but processed for a low volume industry market. The time pressure during its product development is also present but not as harsh as in the high-volume consumer electronics industry. The number of products that are produced annually is normally around one hundred during the first year of release. The products themselves are highly innovative, i.e., the degree of unknown technology used is very high compared with the derivative products.

Table 6.1 Differences between high-volume consumer electronics industry and highly innovative professional product industry

High-volume consumer electronics industry	Highly innovative medical product industry
Higher TTM pressure	Lower TTM pressure
Very limited innovation	Highly innovative
High volume production	Low volume production

The differences mentioned above, especially the degree of innovation, became the major difficulties that this RQM implementation encountered.

Due to the high degree of innovation, almost the entire process steps and product parts were indicated as unknown for the product. Since most of the technologies to be used were still very new to the company, it had no clear idea what would be the potential reliability problems and was also not able to develop any constructive model to estimate the potential problems because there was simply no information available yet. The observations naturally became the obstacles of the RQM implementation there. In the end, the implementation was called off and an analysis was done to understand why RQM could not be implemented there.

Clearly, RQM is not ready yet to be applied for the development of highly innovative products. It was developed based on the experiences in derivative product development. It can recognize and reduce uncertain reliability information involved in a derivative product. The uncertainty is caused when information available somewhere in the process is not with the right people or is otherwise not deployed at the right level. However, in this case, the information was not available at all. This was the reason that RQM could not be implemented as expected without necessary adjustment. The further improvement and generalization of RQM to other types of PDPs are not within the scope of this thesis. They will be discussed as the future research direction in the next chapter.

6.10. Conclusion

This chapter discussed the implementation and validation of RQM in an industrial case. By using RQM the team was able to manage uncertainty in reliability predictions and to prevent related Phase 1 reliability problems in some cases while not in some other cases. Although the awareness of uncertainty in reliability prediction was improved, it was still neglected as product reliability was managed only in one-dimension when using uncertain information. RQM was therefore adjusted. By using default Cp values related to probability of occurrence, it was highlighted to the team that uncertainty should not be viewed as window-dressing in reliability management and actions must be taken to reduce it.

Although initially it was planned to apply RQM five times in the PDP and the actual implementation only took place in three different moments in the process, it was already sufficient for the team to monitor the status of uncertainty management in the PDP. Based on the implementation results, RQM was included in the formal procedure of the CFPDP in the business unit. From then, RQM has been applied there continuously.

Discussions were also given to investigate the feasibility of applying RQM in a company active in the domestic appliances industry and in a radical PDP of producing medical equipment. RQM was proved to be not suitable (yet) for radical PDPs.

Although RQM is only tested in a particular context here because of the research design decision (to prevent, as much as possible, the influence of unpredicted disturbing factors), it does not mean that RQM can be only used in this context. Obviously it would be invalid to apply RQM in any PDPs in any industry as the research problem was identified in a single multinational company. However, it is still possible to apply RQM to CFPDPs in companies that have structural similarities with the company analysed here. According to the case studies reported in (de Graef, 2001), the company analysed here, its business processes and the technology used is not very different from companies active in the same area. Same conclusion can also be drawn from the position of the major companies active in this field on the market. In high-volume consumer electronics industry, there is no clear market leader with respect to product reliability (especially phase 1 failures). In addition, most companies use very similar technologies (same suppliers of same components, similar manufacturing equipment) to develop very similar products through very similar processes. Therefore it is quite likely that RQM can be used to not only the CFPDPs in the company analysed here but also in similar companies active in this field.

CHAPTER 7 CONCLUSIONS AND FUTURE RESEARCH

This chapter is organised as follows. In Section 7.1, major research findings are summarised with respect to the research problem and the two research questions identified in Chapter 3. Section 7.2 evaluates this research. The contribution as well as the limitation of this research is discussed. Section 7.3 gives some conclusions on generalisation of the use of RQM in other types of PDP. Future research directions are proposed in Section 7.4.

7.1. Summary of the Research

In this research, reliability problems in a CFPDP in consumer electronics industry have been analysed. A few important conclusions have been drawn and will be briefly summarised below.

7.1.1. Problem Identification

During this phase, related literature was studied to develop the research focus of this thesis and a proposition was formulated from which a suitable research problem was identified. The major findings are listed below.

PDPs in high-volume consumer electronics industry are dominated by a strong pressure on TTM. Being first in the market gives companies the opportunity to set the standard and to secure a larger market share with increased product revenues from the extended sales life. Early entry into the market also gives companies an opportunity to command a price premium and hence higher profit margin. Reducing the product development time allows companies to start later, with the opportunity to incorporate the latest features and technologies. By reducing TTM, companies can bring more products faster to market. It has been recognised that derivative PDPs can be more easily accelerated than radical PDPs because these PDPs pertain only small incremental changes from existing products and processes. Therefore, reducing product complexity has been considered as one of the acceleration strategies that have been widely discussed in the literature as well as practised in industry. This research project focuses on fast PDPs, derivative PDPs under TTM pressure.

It has been also recognised that constant failure rate model is no longer valid to model product reliability as product reliability does not depend on component reliability alone and it also depends on the PDP that develops the products. Reliability problems from Phase 1 and Phase 2 of the four-phase roller coaster curve are considered as the most relevant problems for high-volume consumer electronics industry. This research project focuses on Phase 1 reliability problems in fast PDPs.

By discussing on four different ways of managing reliability in four types of PDPs, developing derivative products in concurrent PDPs, in which reliability is proactively managed, has been recognised as the most appropriate way to deal with strong TTM pressure. This research project focuses on Phase 1 reliability problems in CFPDPs.

In a CFPDP, it is theoretical possible to predict Phase 1 reliability problems since such a PDP uses known technology to fast integrate mature building blocks. A proposition is therefore formulated:

Since a CFPDP fast integrates mature building blocks using proven technology, there should be very limited unpredicted Phase 1 reliability problems.

However, it has been observed in real life CFPDPs (see Chapter 3 and Appendix A) that there can be many unpredicted Phase 1 reliability problems. As a result, the research questions were derived.

Research question 1: What causes unpredicted Phase 1 reliability problems in CFPDPs?

Research question 2: How can these problems be prevented?

7.1.2. Research Question1: What Causes Unpredicted Phase 1 Reliability Problems?

In order to answer research question 1, the earlier cases were studied further in order to identify the root causes of unpredicted reliability problems in the PDPs. In Chapter 4, it was observed that FMEA was used to manage reliability problems in the PDP. By analysing the related reliability information flows, the root causes of unpredicted reliability problems were identified. The most important findings from the case study are summarised below.

It was observed that a mismatch between the ways that the customer and the business unit checked compliance with the product requirements resulted in many unexpected reliability problems. Obviously this problem is a process-flaw related problem. It is also related to Phase 1 of the roller coaster failure rate curve. Theoretically, it should not occur in the first place because of the characteristics of the Phase 1 problems in CFPDPs. Information about this mismatch was available in the PDP, but, it was not used when making prediction and the business unit still considered that a related cheaper component was responsible for this problem. As a result, unpredicted reliability problems appeared. In addition, these problems were found not unique to the product. It was observed that four different types of reliability problems were managed in the PDP

- PMP: when the reliability information used in reliability prediction was very certain, the associated reliability problems were predicted and prevented or accepted.
- NP: when the reliability information was totally irrelevant, the predicted reliability problems added “noise” in reliability prediction.
- RMP: when the required reliability information used in reliability prediction was uncertain, the related reliability problems were not predicted at the right time in the PDP but these problems eventually were resolved in the PDP by negotiating with the customer.
- PPP: when the reliability information was uncertain, the associated reliability problems were poorly predicted (PPP) and became unpredicted reliability problems reported by the customer.

The situation, which the required information is not used at the right moment in the PDP although such information is known, is referred to as the existence of uncertainty in the information in this thesis. It has been concluded that unpredicted reliability problems were caused by uncertain information in reliability prediction.

The case results showed that FMEA is unable to predict relevant reliability problems using uncertainty information. Such conclusion leads to a reconstruction of research question 2.

7.1.3. Research Question2: Is It Possible to Define a Method to Manage Reliability Information in CFPDPs including the Aspect of Uncertainty?

In order to answer this question, a reliability management method, RQM, was developed. In order to enable the prevention of unpredicted Phase 1 reliability problems, by using RQM the following formal requirements should be fulfilled.

- *Classifying uncertainty when predicting reliability*

  This research project has identified three different types of information that can be used in reliability prediction. The first type of information is from existing products and production process as a CFPDP uses proven technologies to quickly integrate mature building blocks from existing products and production process. This type of information is thus very certain. The second type of information is based on computer simulations or real experiments when improving product reliability. This type of information is medium certain. The case study reported in Chapter 5 indicated that there is one more type of information, which is very uncertain. Reliability prediction based on these three types of information thus also consists of three different levels of uncertainty. By using RQM, uncertainty in reliability prediction can be therefore classified.

- *Prioritising uncertainty improvement activities*

  It was learnt that FMEA focuses on only improving probability of occurrence of potential reliability problems. Uncertainty in reliability prediction is neglected. By using RQM, it is encouraged to reduce uncertainty involved in reliability prediction before reducing the probability of occurrence. As a result, it is less likely to have unpredicted Phase 1 reliability problems.

- *Monitoring uncertainty in a CFPDP*

  In a CFPDP, potential reliability problems should be identified proactively even when using highly uncertain information in reliability prediction. By using RQM very early in the PDP, potential reliability problems and their associated uncertainty levels can be predicted. Necessary early design changes, and reliability test plan can, therefore, be derived to prevent or resolve these problems. The results of reliability-related activities (e.g., FMEA, and reliability tests) can be used to update the RQM continuously during the PDP. By doing so, the status of the uncertainty in reliability prediction can be monitored during the process.

- *Optimising product reliability*

  By using RQM to prioritise customer requirements and perform diversity analysis between the prioritised customer requirements and the existing products and production process step, the PDP is able to define incremental changes that are necessary to satisfy customer requirements. Computer simulations and real experiments are recommended to introduce these changes in a way that enables that product reliability can be optimised.

From a method point of view, being able to classify, prioritise and monitor uncertainty in reliability prediction, RQM promotes effective prediction, reduction and management of unpredicted reliability problems. From a process point of view, RQM can be implemented in the very early stage of the PDP and updated continuously during the PDP. Consequently, potential reliability problems can be identified proactively and correctly when highly uncertain reliability information is used in the prediction. Necessary early design changes, and reliability test plan can be derived to prevent these problems accordingly. RQM can also be updated continuously based on the results of reliability related activities during the PDP. It is expected that by using RQM Phase 1 reliability problems can be well prevented.

After RQM was developed, it was tested in a real life CFPDP. Ideally, it should be tested in the same case where the research problem was identified. However, it was practically not possible, as we cannot develop a product again that was already in the market. To prevent unnecessary and unexpected disturbing factors, it was decided to test this method in a very similar case, in which the product was very close to the previous product, the PDP was the same as the previous one, the development team was also the same as the previous one, and it was possible to apply this method through the entire PDP.

It was planned to apply this method five times in the PDP. However, due to some unplanned changes in the project team as well as the very tight project schedule, this method was applied three times in the PDP. However, the implementation results have shown that such implementation did not affect the validation of this method. It was demonstrated that when uncertainty was well managed by applying this method, the team was able to predict and prevent some Phase 1 reliability problems. However in two other typical cases the team still had difficulties to manage uncertainty in reliability prediction even by using RQM. As a result, unpredicted problems appeared. One case happened when predicting the probability of occurrence of potential reliability problems using highly uncertain information. The team always intended to assign a very low figure to these problems (unless experiences showed that a high value was necessary) so that it could skip these problems and concentrate on more certain problems with higher probability of occurrence. The other case happened when predicting the probability of occurrence of potential reliability problems using model-based estimate. The team treated the degree of uncertainty related to a model-based estimate and in a validated estimate the same although they are different in nature. One is based on limited number of samples and simplified models while the other is based on valid information from existing products and production process. Such difference led to unpredicted Phase 1 reliability problems. In order to overcome these two situations, two guidelines were given to use default Cp values to interpret rough estimate and model-based estimate with their associated uncertainty level. By doing so, it was possible to predict and prevent Phase 1 reliability problems.

The company in which the research was conducted was very satisfied with the first implementation results of RQM. As a result, RQM has been included as part of its formal PDP procedure.

7.2. Research Evaluation

Based on the conclusion of the research results three main contributions are summarised below.

♦ In CFPDPs, uncertainty in reliability prediction can lead to unpredicted Phase 1 reliability problems.

Based on the literature study it has been concluded that theoretically there should be very limited unpredicted Phase 1 reliability problems in CFPDPs as they fast integrate mature building blocks using proven technologies. However, empirical studies have demonstrated that there can be many unpredicted Phase 1 reliability problems by using uncertain information in reliability prediction. Based on this the first research question is answered.

♦ Uncertainty should be reduced first when preventing unpredicted Phase 1 reliability problems caused by uncertainty in reliability prediction.

It has been demonstrated from the field case in Chapter 4 that using FMEA is not sufficient to predict and prevent unpredicted Phase 1 reliability problems. This is because such methods concentrate mainly on improving the probability of occurrence of potential reliability problems but neglecting the associated uncertainty. In order to predict and prevent unpredicted Phase 1 reliability problems, it is thus necessary to reduce the degree of uncertainty first.

♦ By using RQM it is possible to predict and prevent unpredicted Phase 1 reliability problems in CFPDPs.

RQM was developed according to a number of formal requirements to manage uncertain information in reliability prediction so that unpredicted phase1 reliability problems can be predicted and prevented in CFPDPs. The process of RQM has a close relation with the process flow of a CFPDP. By using RQM, uncertainty reduction related development activities are the priorities in the PDP.

Based on the implementation results, it was evaluated and further adjusted. It has been concluded that it is possible to predict and prevent those unpredicted problems by using this method. This answers the second research question.

7.3. Generalisation

This research project was carried out on three CFPDPs in one single multinational company. Therefore, it would be statistically invalid to generalise the subsequent research results to PDPs in general.

It is, however, possible to do some generalisation by using structural similarities between the company analysed here and other companies active in this field. The company analysed here, its business processes and the technology used is not very different from companies active in the same area. Although this is evident from literature (de Graef, 2001), it can also be derived from the position of the major companies active in this field on the market.

In high-volume consumer electronics industry many companies fiercely compete. Although, as demonstrated in this thesis, managing phase 1 reliability problems is very important for reaching TTM, there is no clear market leader with respect to product reliability (especially phase 1 failures). In addition, most companies use very similar technologies (same suppliers of same components, similar manufacturing equipment) to develop very similar products through very similar processes. Therefore it is quite likely that the findings of this thesis can be extrapolated to not only the company analysed here but also to similar companies active in this field.

Using the structural similarities, it should be possible to generalise the research results. Using RQM in a different situation, however, will be more difficult. It is known that RQM was developed to manage uncertainty in reliability prediction in a CFPDP. In Chapter 6, an effort of applying RQM in a non-derivative PDP was reported. It was planned to use RQM in a highly innovative (R&D) product from a company, which produces professional medical equipment for hospitals. It was concluded that RQM was not ready to be applied there as RQM was developed based on the experiences in derivative product development. The uncertainty in reliability prediction occurs when the required information is not available at the right place or not used correctly in the PDP, but the information itself is always available somewhere in the process because of the characteristics of derivative products. In the case of highly innovative products, the required information can be not available at all. That was why that RQM could not be implemented as expected unless necessary adjustment is made.

7.4. Further Research

This research project has been conducted in a well-defined scope in order to complete a PhD thesis, but the research itself will not just end there. In the following, potential future research directions are discussed.

7.4.1. Applying RQM in a Distributed Product Development Environment

As discussed already in Chapter 2, globalisation is an unavoidable trend of PDPs. As a result, more and more CFPDPs are distributed in different places (cities, countries, or even continents), but not necessarily in a single organization as certain activities can be outsourced (Rothery and Robertson, 1995). The case results reported in Appendix A showed that uncertainty in reliability prediction also exists in distributed CFPDPs and it can also cause unpredicted Phase 1 reliability problems. Petkova and Sander (2000b) argued that outsourcing makes extra demands on the completeness and clarity of the specifications at the outsourcer as well as at the suppliers. It is known that incomplete specifications can cause Phase 1 reliability problems. The question is now whether RQM can be applied to prevent unpredicted Phase 1 reliability problems and how RQM should be applied there. From a method point of view, in principle, RQM can be applied to predict unpredicted Phase 1 reliability problems when a CFPDP consists of outsourced or distributed activities. The main discussion should be focused on how to apply RQM from a process point of view. As RQM is to be used at the very early phase of the PDP and to be updated continuously during the PDP, further research directions for a CFPDP that consists of outsourced or distributed activities should then focus on

- How RQM should be managed in the PDP
- Who should be responsible to the overall performance of RQM
- How RQM results should be interpreted at the outsourcer and at the suppliers, etc.

Then RQM can be further adapted to the requirements of different organisational hierarchy structures of a project team, to the requirements of different structures of a PDP, and to the requirements of different supplier chains. The practical implementation of RQM can be also enhanced. To drive this research further, necessary cooperation with researchers who specialise in Organisational Science, New Product Development, as well as Supply Chain Management is obviously essential.

7.4.2. Applying RQM to Handle Uncertainty in Customer Requirements

The case study results show that most of Phase 1 reliability problems were related to mismatch between producer specification and customer specification. Uncertainty in reliability prediction was always related to product information (i.e., producer specification). RQM was thus developed to handle this type of uncertainty. Uncertainty related to customer specification was not considered. However, the trend of increasing customer requirements (Wheelwright and Clark, 1992) suggests that customer specification most likely also contributes to uncertainty in reliability prediction. A possible future research direction can take into account the uncertainty related to customer specification in predicting reliability.

7.4.3. Applying RQM to Include Uncertainty from the End-user

This research project only studied reliability problems reported by the customer in a CFPDP of a business-to-business manufacturer. Information from end users was not included. Current literature suggests that there is very limited useful information available from the end user that can be used to improve product reliability. This is because most of the information is logistics oriented and the motivation of collecting such information is not to improve product reliability but to save cost and time (Petkova et al., 2000; Molenaar et al, 2002). In principle, RQM can still be applied there to manage uncertainty theoretically. However, reducing uncertainty in such information cannot be achieved by applying RQM alone. Petkova (2003) suggested a field feedback system to collect reliable field information for the purpose of improving product reliability. Integrating her research results into RQM can enhance uncertainty management in CFPDPs.

7.4.4. Applying RQM with High Degree of Innovation

One of the major trends in PDPs is that the degree of innovation progresses in a dramatic speed (Birnbaum, 1998; Nijssen et al., 1993; Wheelwright and Clark, 1992). When the degree of innovation increases in a PDP, generally speaking, the degree of uncertainty in the information that can be used to predict reliability also increases. However, this uncertainty is different from the uncertainty exist in CFPDPs as the former is due to totally unknown technologies and the latter is due to poorly deployed known information. Therefore, as demonstrated already in Chapter 6, RQM cannot be applied immediately in a radical PDP unless necessary adjustment is made. This discussion leads to one possible future research direction: how to adjust RQM so that it can be applied in radical PDPs to manage reliability. A few interesting questions for further discussion can be:

- What should be designed additionally in RQM so that the lack of information due to totally unknown technologies can be also managed?
- What additional development activities should be planned together with RQM? (different way of testing, build early prototypes?)

7.4.5. Computerising RQM

An Excel-based spreadsheet was developed to organise the information generated by a RQM session. It was suggested that RQM should be used very early in the PDP and generate input to following reliability related activities and it should also be updated based on the results of reliability related activities. At the moment, filling up the spreadsheet and update RQM results are still done manually. The advanced development of computer, internet and web-based techniques makes it possible to automate the filling up and updating procedure of RQM and to link RQM as part of the computer based database in the business environment for long term improvement purpose.

APPENDIX A RELIABILITY PROBLEMS IN A CFPDP OF A SPEAKER BOX PRODUCER IN CHINA AND MALAYSIA

A.1 Introduction

This appendix presents the results of a second[8] industrial case study. It was performed as one of the case studies in this research project to identify and analyse the unpredicted Phase 1 reliability problems in CFPDPs. It was conducted in a different business unit in the same multinational company.

A.2 The Business Unit, its Products and its PDPs

The business unit in the company where this case study was conducted is active in the area of sound system. It shares the common customers with the business unit discussed in chapter 3 and 4. Also this case study was performed in competitive market conditions where the short TTM is one of the major constraints. Therefore this business unit uses a CFPDP with incremental product innovation. In the market where this company is active it is common to introduce three generations of a product platform each year. As a result, this business unit has to follow this trend and develop many derivative products based on existing product platforms. By implementing concurrent engineering, it has been able to reduce the length of its PDPs significantly (from 1 year to 23 weeks).

The product, analysed in this case study, is a speaker box. As a derivative product, it has the same functionality as the platform product and it used most mature building blocks from existing products. The main driver to develop such a derivative product was to reduce product cost. The only change in this product was that cheaper materials were used.

[8] In the context of this thesis a total of five PDPs has been analysed; cases 1, 2, 3 and 4 deal with CFPDPs, case 5, as addressed in Chapter 6 uses a breakthrough PDP. Since the conclusions of case 3 are very similar to the case addressed in Chapter 3 and Chapter 4 and the case addressed in this appendix, they are not further addressed in this thesis for the reason of company confidentiality. Full details, however, are available with the author. Case 4 is the implementation case of RQM addressed in Chapter 6.

The case study, addressed in this section, also meets with the requirements listed in chapter 3. Therefore, it is also suitable to conduct a case study with this product in its PDP in this business unit to verify the proposition formulated in Chapter 2.

A difference with the case addressed in chapter 3 is the fact that in this case the development activities were distributed in three different locations as the department of development was located in Malaysia, the department of engineering and purchasing in Hong Kong, China, and its production is in Shen Zhen, China (see Figure A.1).

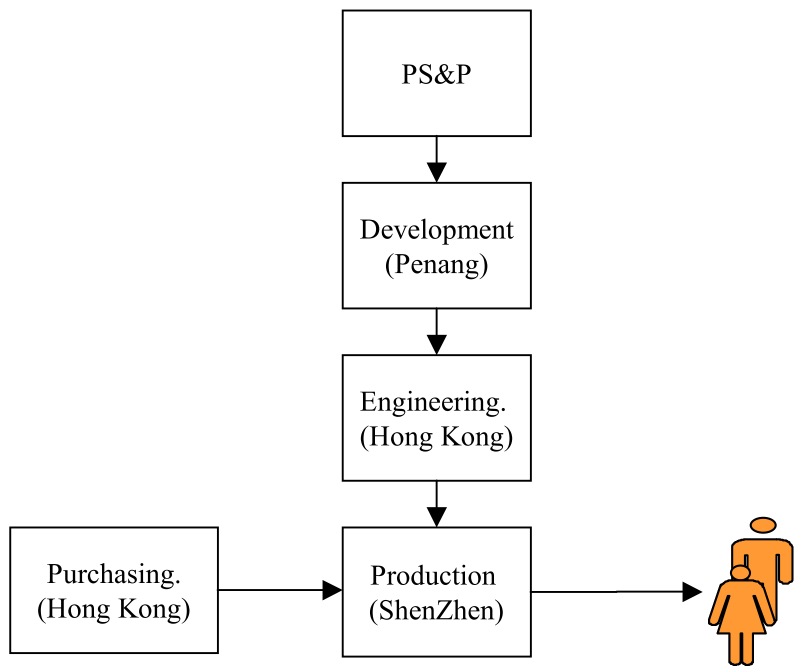

Figure A.1 The distributed PDP

A.3 The Reliability Problems

In the year of 2000, an MIR assessment (see Appendix B) was performed to investigate Phase 1 reliability problems in the selected CFPDP. During the assessment, formal interviews were used to collect data about reliability problems in the PDP. 16 key persons including 9 managers and 7 engineers from Product Strategy & Planning (PS&P), Design, Engineering, Production and Quality were interviewed. The observations and results analysis of this case study are briefly discussed below

Like in the case study of chapter 3, there are two principal sources of information (from customers and from end-users) about actual product reliability problems since it is also a business-to-business manufacturer. During the analysis, similar to the case addressed in Chapter 3, it was learnt that the information collected from end-users was less relevant to the real product reliability problems compared with the information collected from the customer. The information collected from end-users by the service organisations was sent to the business unit via its customers. This information was collected within product warranty time in the following way. Authorized service centres or dealers repaired or replaced the field returns and recorded the number of spare parts used or the number of repairs in a kind of Job Sheets. These Job Sheets were sent to National Service Organization (NSO) of this company for claiming service charge. NSO requested service centres to study the Job Sheets and help decide whether the claiming was valid. Then service centres compiled a field report based on the Job Sheets. The customers received the field report from service centres and distributed them to their suppliers. It was learnt that after the production in the customers, it took about two months or more to ship the manufactured products to the targeted markets and one-month to sell them. It then took another three months to start getting some reliability information from the end-users. In total, it took about six months to start getting some feedback, but the entire production only lasted for 4 to 5 months. Furthermore, 9 months later after the first shipment, service centres could start to compile the field report because only by then there was sufficient information available from the end-users. The customers tried different ways to accelerate the process that sent back the information to the business unit from the end-users. As mentioned earlier, the information from the end-users collected by the service centres or dealers was mainly related to the number of used spare parts or the number of repairs, which was very logistics oriented. It resulted in a situation that sometimes a key component was replaced or repaired because the reported fault could not be reproduced and a solution had to be given anyway. The real root causes of the reported faults were unknown. With the current field information, it was not possible to figure out why products failed and how to prevent them from failing in the future. Compared with the information collected from the end-users, the information collected from the customer was more reliable. Since there are normally standard procedures agreed between the business unit and its customers for collecting and reporting this information, this information is usually communicated between them at a regular basis. In addition, reliability problems reported by the customers were dominated by early failures that interest this research project.

Therefore it was decided to analyse the reliability information from one of the customers in order to see whether it was possible to apply also in this case the proposition formulated in chapter 2. A large number of Phase 1 failures (cosmetic problems) were found as the dominant reliability problems. On average, more than 50% of the products were rejected at the customer’s factory related to this problem, which was much higher than the intended target.

Reliability testing in the development phase was done based on the company standard and not on actual customer requirements. Since a new material was used, it was known that the cosmetic problem might become a critical problem. A remark was given that the material was considered new to this speaker box but not to the company since it had already been used in other products before. However, the test specification defined in the standard did not take this factor into account. This was because it took very long time to keep the standard up-to-date. The customer also performed reliability tests regarding cosmetic problems. However, its way of testing was totally different. Due to the mismatch between the test specifications in the business unit and its customer, the customer rejected many products with the cosmetic problem. According to the description of the four-phase roller coaster failure rate given by Brombacher and de Graef (2001), obviously, this PDP had many unexpected Phase 1 reliability problems.

Together with the results of the other case study discussed in Chapter 3, it can be concluded that there can be many unpredicted Phase 1 reliability problems in CFPDPs. Such conclusion leads to the research problem statement and the formulation of research questions that are researched in this research project.

A.4 The Root Causes of the Reliability Problems

The cosmetic problem was not a new problem. It was known to project management that this problem might be critical to the product due to the use of a new material. However, the material was just “new” to this product. It was used before in other products and it was considered as known. It was also known that the customer tested this problem differently from the business unit, but such information was not used when predicting product reliability. One of the main reasons was that the product development activities were distributed in three different locations. Sometimes, one piece of information was known to the entire business unit but just available to one location and not available to other locations where it was most needed. Thus, although a lot of tests were done in the business unit and by the customer, there were still many unpredicted cosmetic problems reported by the customer. Figure A.2 schematically displays the reliability information flows observed in the PDP.

This problem could be potentially predicted if the information about the different way of testing by the customer could be used in reliability prediction. Although the information was available there, it was not used at the right moment in the PDP. In short, the cosmetic problem was caused when the required information was not used at the right moment in the PDP. Uncertainty in reliability prediction was found as the root cause of the unpredicted Phase 1 reliability problems in this case study.

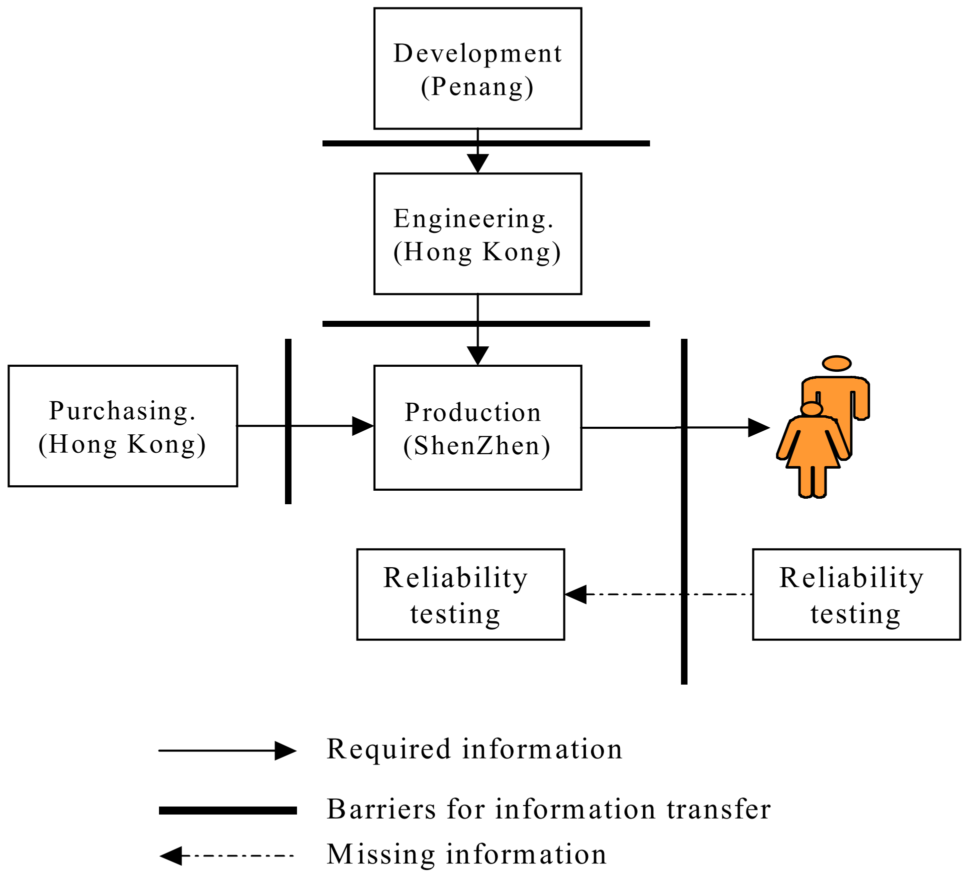

Figure A.2 Analysis of the reliability information flows

A.5 Conclusion and Discussion

Together with the results of the other case study discussed in Chapter 3 and 4, it can be concluded that there can be many unpredicted Phase 1 reliability problems in CFPDPs and they are caused by uncertainty in reliability prediction. Such conclusion initiates the development of the reliability prediction method in Chapter 5.

However, the developed reliability prediction method was not implemented and evaluated in this business unit. There were two reasons. One reason is that although the reliability prediction method was developed to cope with uncertainty in reliability prediction, it was not yet suitable to be applied in a distributed CFPDP as there were still many open questions, including:

- Who should own this method in the PDP?
- Who should be responsible to the input and output of this method?

How to implement RQM in a distributed CFPDP is then considered as one of the future research directions discussed in Chapter 7. The other reason, also the practical reason of not implementing RQM in this business unit, is that after the case study, some business changes took place. It was decided that the sub-unit in Malaysia would focus more on multimedia products and the sub-unit in Hong Kong and ZhenZhen would focus more on audio products.

APPENDIX B THE MIR ANALYSIS USING FORMAL INTERVIEWS

This appendix describes the structure of using formal interviews in an MIR analysis. The MIR analysis described here is based on the course materials of the TU/e course “Lifecycles of products and production systems” (IFF10). This structure way has been partially developed and applied in the field cases addressed in this thesis (see Chapter 4 and Appendix A). The generic steps in conducting the MIR analysis are discussed first, followed by the derived structure of using formal interviews to perform the MIR analysis in these field cases.

B.1 The MIR Analysis

By analysing the lifecycle of a product or a process installation and identifying missing or incomplete reliability-related information flows, the Maturity Index on Reliability (MIR) concept (Brombacher, 1999) can be used to measure the capability of an organization on controlling reliability-related information. In the MIR analysis, two steps need to be taken:

♦ Modelling the lifecycle of a product
♦ Analysing the lifecycle of a product based on the MIR concept.

B.1.1 Modelling the Lifecycle of a Product

Modelling the lifecycle of a product can be illustrated by modelling each process in the lifecycle as a network of sub-processes or activities that are interconnected. As a flowchart expresses the sequence and logic of procedures using symbols to represent different types of input/output, processing, and data storage, it is used as a graphical representation of the MIR analysis to display the different processes in the lifecycle. By doing so,

♦ communication procedures, controls and the sequence in which they occur can be visualised;
♦ the actual vs. ideal flow of a process can be compared to identify improvement opportunities;
♦ the activities that may impact the process performance can be identified and examined;

- a better understanding of the complete process can be achieved;
- the objectives, documentation and information flows in the process can be connected.

As a result, in the MIR analysis, the product or process lifecycle is converted to a flowchart, which consists of one or more of the following items

- the phases;
- the processes;
- the information flows;
- the learning cycles.

In a product lifecycle a phase can be seen as a transformation where input is transformed into output. A phase has one or more phase(s) (supplier(s)) which supply the input needed in the phase. For a phase it is known what must be achieved (objectives), how this should be achieved (activities/requirements) and why this should be done. Also the phase is connected to other phases (customers) that use the information created during the phase (see Figure B.1). The input and output for these phases can be databases, documents or results of discussions. It is also possible that required information/data is not directly related to/created in the process lifecycle. This information/data comes from outside the process and is called external data. All information used and created should be unambiguous.

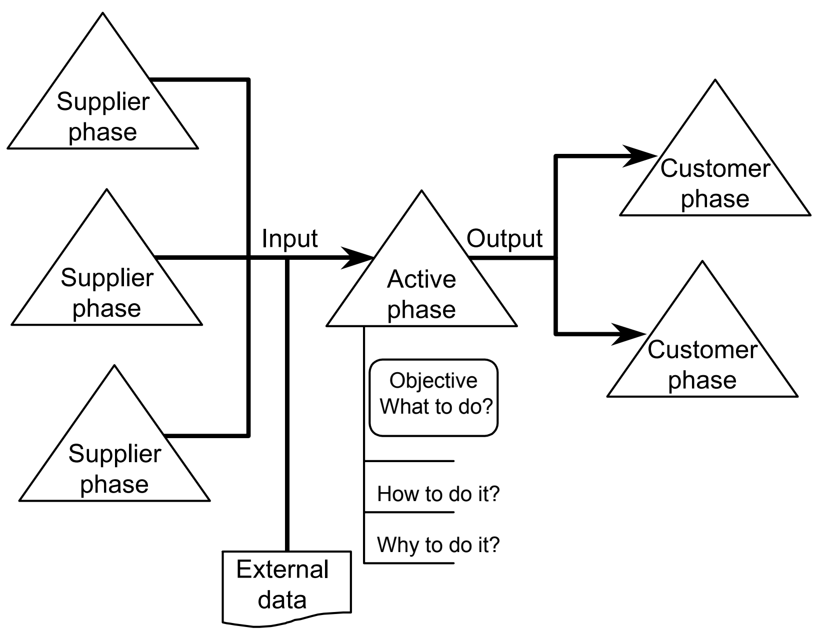

Figure B.1 Lifecycle phase with input, output and objective

The complete product lifecycle consists of a lot of these phases. All these phases together form a process. A process can for that reason be seen as a set of interrelated activities aimed at generating a certain process output. In the process the phases can require output from previous phases to fulfil the objectives of that phase or from outside the process. The information generated during the activities of a phase can be needed for subsequent phases to fulfil their objectives or for other processes. Output of the phases can stay in the process but can go also to the outside. By combining phases, inputs and outputs a flowchart can be built with all information flows necessary to fulfil the objectives of a subsequent phase. These information flows are the set of activities with their connected in/outputs required to obtain a certain process output. These information flows are important for the analysis. On the basis of these flows it is determined whether the product lifecycle is complete or not. Also the MIR level is assigned. From all information that is created and all activities that are done it is possible to learn. In the process, learning cycles should be included. Learning cycles can be seen as a mechanism that enables an organization to observe, to explain and to control differences between target process output and actual process output. The target situation for a product lifecycle includes all these elements. For the ideal product/process lifecycle see the schematic representation in Figure B.2.

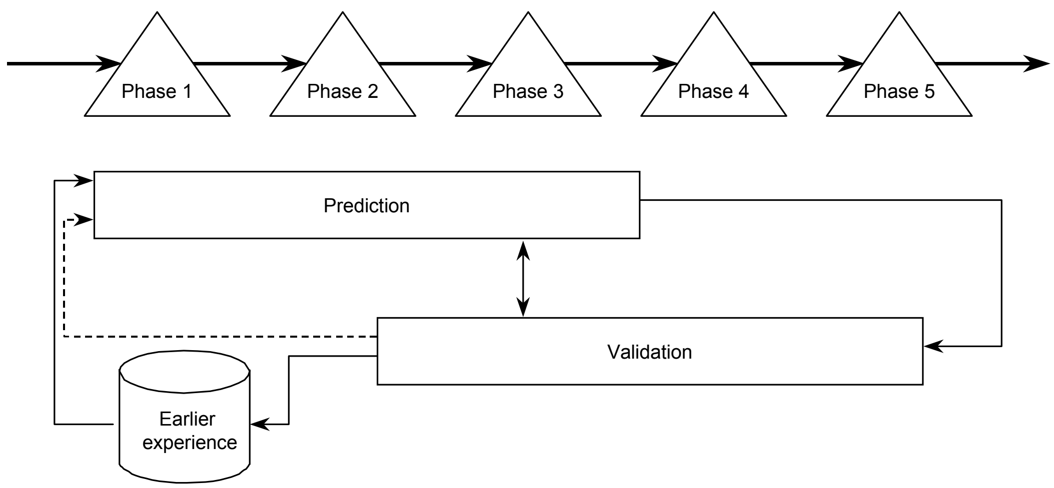

Figure B.2 Schematic presentation of the ideal flow (Brombacher, 1999)

To identify all the process phases and information flows several steps should be taken. First determine which process has to be considered and the result that must be achieved by this process. Then determine the phases with related objectives and activities and how they follow each other. All needed input must be uncovered and the output must be known. Confirm that the input of a phase is the output of the previous phase that must supply this input. Confirm also that the created output is the input that is needed in the connected phase. Assign the information flows between the linked activities. Identify the outputs that flow to the outside of the process to another process and the input from outside the process. At last add the learning cycles to the process. At this moment the flowchart is completed and it is possible to analyse the product lifecycle to identify missing or not complete items.

B.1.2 Analysing the Lifecycle of a Product based on the MIR Concept

Depending on the information flows that are realized in modelling the lifecycle of a product it is possible to assign them MIR levels based on the MIR concept. The four-level scale, which reflects the increasing capability of an organization to analyse, predict and improve the reliability of its current and future products, is the following:

1. *Quantification* (measured): The business process is able to generate quantitative information, on a per-product basis, indicating the number of failures in the field and production.
2. *Identification* (analyzed): The business process is able to determine the primary and secondary location of failures:
   - Primary (organization): Location of the cause of the failure within the business process.
   - Secondary (position): Location of the failure within the product.
3. *Cause* (controlled): The business process is able to generate detailed information for all dominant failures on root-cause level. This can be translated into repairs/modifications in current products and anticipated risks for future products.
4. *Improvement* (continuous improvement): The business process is able to learn from the past in installing business processes and working methods to anticipate reliability risks for future products and eliminate these risks as part of new product creation.

It is important to stress that complex business processes comprehend a wide variety of information flows. These flows may be equipped with reliability-related information of different categories. With respect to the wide variety of existing information flows as part of the considered business processes, every information flow needs to be considered separately. For each flow, its actual MIR level, its required MIR level and the required level of information shall be determined. Such a reliability-related information flow analysis will reveal discrepancies between actual and required MIR levels. Depending on the specific purpose of each considered information flow the MIR analysis decides what is its required MIR level and what is its actual MIR level.

Various MIR studies (Sander and Brombacher, 1999; Brombacher and de Graef, 2001; Knegtering, 2002) carried out during a number of years, have resulted into new insights concerning the application of MIR levels. Whereas initially a strong focus existed on analysis of the business processes of an organization as an integrated whole, today a more differentiated attention is given to the analysis of specific information flows. Evidently, this has also resulted in adaptations to the definitions of the MIR levels. Below, an overview of the 5 different categories of information flows is given. These definitions were used in the case study reported in Chapter 4 and Appendix A.

Table B.1 Adapted definitions of MIR levels (see course materials of the TU/e course "Lifecycles of products and production systems" (IFF10))

Category	Description of reliability problem handling	MIR
-	No information flow exists.	0
Explore	Information on what goes wrong, where and when.	1
Explain	Information on where (organisational location) does it go wrong and how and why does it go wrong. (technical location?)	2
Control	Information on how to correct and maintain the reliability performance. (root cause)	3
Prevent (Predict and anticipate)	Information on what might go wrong in future products, processes or services, and information on how potential future problems can be prevented or averted.	4

B.2 A Structure to Analyse Reliability Information Flows Using Formal Interviews

As discussed above, the MIR analysis has proven to be a very useful method for analysing the lifecycle of a product (Brombacher, 1999). The flowchart gives a clear overview of a product lifecycle. It shows all relevant reliability information flows that have to be achieved to operate in a right way. Especially, with regard to reliability management the MIR concept offers an approach to analyse the reliability of a product through analysis of the reliability information flows in a PDP (Brombacher, 1999). Four MIR levels are distinguished, and describe to what extend product reliability is managed in a PDP. Based on the way that reliability information flows are modelled in an MIR analysis, a structure of using formal interviews to perform the MIR analysis in a PDP was partially developed and applied in the case study (see Chapter 4 and Appendix B). A few important steps were identified. They are listed in Table B.2.

Table B.2 MIR analysis using formal interviews

MIR analysis using formal interviews	
Step 1	Identifying the product and the PDP to be studied
Step 2	Identifying reliability-related activities
Step 3	Identifying the candidates for the interviews

Step 4	Conducting interviews based on the formulated Interview questions
Step 5	Developing activity flowchart based on the interview results
Step 6	Identifying the reliability information flows
Step 7	Crosschecking the reliability information flows with other sources of information (e.g. documents and archives)
Step 8	Evaluating the reliability information flows based on the MIR concept
Step 9	Reporting

The above table clearly illustrates the structure of using interviews to perform an MIR analysis. Steps 1 and 2 define the scope of the reliability information flows to be analysed. As mentioned earlier, the MIR concept can be applied to analyse the reliability of a product through analysing the reliability information flows in a PDP. By identifying the product as well as the PDP to be studied, the overall scope of the analysis can be defined. In addition, the reliability information flows depend very much on the reliability-related activities in the PDP. By identifying the reliability-related activities in the PDP, the scope of the analysis is further restricted to the information flows generated by these reliability-related activities. These activities can be identified based on the description of the PDP or project planning documents. Steps 3 and 4 concern the way of conducting interviews. The people to be interviewed are those who perform the reliability-related activities. People from both the management level as well as the engineering level who are involved in one or more reliability-related activities are invited for the interviews. By doing so, it is possible to verify the interview results within one activity. Verification was also done along the PDP. Between two different connected activities, the input to the subsequent activity is always verified with the output of the current activity. By doing so, it is possible to collect multiple sources of evidence. As the objective of conducting these interviews is to analyse reliability information flows, a number of aspects need to be considered in the interviews, including:

- Which activity does the interviewee perform?
- What are his experiences and expertise in performing this activity and other related work?
- What is the objective of this activity?
- What is the relation between this activity and the reliability of the product?
- What information is necessary to perform this activity?
- What methods and tools are used to perform this activity?
- What information is generated by this activity?
- Who will use the generated information?

Steps 5, 6, 7 and 8 focus on analysing the interview results. Based on the interview results, the reliability-related activity model is developed and the reliability information flows in the PDP are created. The validity of these information flows can be further verified with other sources of information, including documents and archive data. Based on the four MIR levels, these reliability information flows are also evaluated. Step 9 concludes the analysis and generates the report. It is important to note that a company will not pass or fail the interviews. The results of the interviews are summarised in a report and this report is presented to the company involved. The information obtained from the interviewees is treated confidentially. The final results are also treated confidentially and they are only available to the company involved.

APPENDIX C PREDICTING PRODUCT RELIABILITY BY USING FMEA

In this appendix, it is briefly discussed that how FMEA predicts product reliability. As there are many variants of FMEA (Lewis, 1996) and the FMEA used in the test case is an adapted version, the general FMEA process is discussed first, followed by a discussion of the adapted FMEA used by the company analysed in the test case in chapter 4.

C.1 The General FMEA

The FMEA procedure was well developed and documented in the military handbook (MIL, 1988) and as a military standard (MIL, 1980) and industry standard (BS5760, 1982). It was first appreciated in the aerospace, nuclear and electronic industries in the 1960's and the automotive industries in the 1970's (Kara-Zaitri et al., 1991; Dale and Shaw, 1990). The International Electro technical Commission (IEC) 60812, "Analysis techniques for system reliability-procedure for failure mode and effects analysis (FMEA)", provides the instructions of analysis procedure and an example of a standard FMEA worksheet (Table C.1). There are in general two phases in the FMEA process. The first phase is to identify the potential failure modes and their effects. The second phase is to perform criticality analyses to determine the severity of the failure modes. At the second phase of FMEA, each failure is ranked according to a criticality method or a Risk Priority Number (RPN) method (Onodera, 1997). A Risk Priority Number (RPN) is often calculated as a product of the severity number, the probability of occurrence and the probability of detection while a criticality number is calculated as a product of the severity number and the probability of occurrence. The most serious failure has the highest rank and is considered first in the design revision. The design is revised to ensure that the probability of occurrence of the highest ranked failure is minimized.

Table C.1 Standard FMEA worksheet

Equipment name	Function	Failure mode	Failure causes	Failure effects	Failure detection	Failure probability	Criticality

C.2 The Problem of Using Criticality and RPN

As discussed, FMEA is a bottom up technique that is very effective in identifying critical reliability problems. It can be described as a systematic way to identify and evaluate the effects of different failure modes, and to determine what could eliminate or reduce the probability of failure. It can be very effective but there are also limitations. Here the problem of using criticality and RPN is discussed.

FMEA is primarily qualitative in nature, although some estimates of failure probabilities are often included (Lewis, 1996). Criticality and RPN are just used to assist the decision process. The decision in FMEA to reduce potential failure modes should not be simply based on the criticality figure or the RPN figure because they can cause confusion. Taking the evaluating tables (Table C.2, Table C3, and Table C.4) of severity, probability of occurrence and the detection probability provided by (Onodera, 1997), an example is given here to illustrate the problem of using RPN and Criticality in FMEA. Given two failure modes, failure mode A and failure mode B, it is to decide which failure mode is more serious by using the RPN. If failure mode A has a level of severity 8, a level of probability of occurrence of 2, and a level of detection probability of 2, its RPN number is then 8*2*2=32. If failure mode B has a level of severity 2, a level of probability of occurrence of 8, and a level of detection probability of 2, its RPN number is then also 2*8*2=32. According to the RPNs the two failure modes are equally important. However, in nuclear type of industry where safety is of the great importance, failure mode A may be more important because it has a higher severity level; in the high-volume consumer electronics industry, failure mode B may be more important since it has a higher probability of occurrence and it is more likely to occur. Therefore, making the decision on which of the two failure modes is the more important one should not be based on the RPN alone, also the constituting figures should be taken into account.

Table C.2 Evaluating tables of severity

Level	Fundamental evaluation
10	Catastrophic
8	Major
6	Severe
4	Minor
2	No effect

Table C.3 Evaluating tables of probability of occurrence of failure mode

Level	Fundamental evaluation
10	Very high
8	High

6	Medium
4	Low
2	Very low

Table C.4 Evaluating table of detection degree

Level	Fundamental evaluation
10	No detection before failure
8	Detectable with final test
6	Detectable with assembly test
4	Detectable with system test
2	Detectable at part level

C.3 The FMEA Used in the Test Case

In order to avoid the confusion of using RPN types of quantitative figures in FMEA, it was decided not to use these figures in the FMEA at the company where the test case reported in Chapter 3 was performed. In stead, a two-dimensional metric is used to rank potential failure modes: the gravity factor and the evolution factor in the FMEA. The gravity factor and the evolution factor have already been described in Chapter 4. They are also listed in Table C.5 and Table C.6 below.

Table C.5 Evaluating table of severity

Gravity factor	Fundamental evaluation
S	non-conformity with safety standard /other safety requirement
A	a problem that results in a not producible or not saleable product
B	a problem that results in a product that can be produced but with big problems or will not be accepted by a critical customer
C	a problem that results in a product that can be sold or produced with minor difficulties
D	a problem accepted by management – no activities will be started to reduce or eliminate this problem

Table C.6 Evaluating table of evolution

Evolution factor	Fundamental evaluation
4	cause not known
3	solution not known

2	evaluation not yet positive
1	solution not yet introduced
0	solution introduced (Generally speaking, if the evolution factor of a reliability problem is greater than 0, it means that this problem is not yet resolved.)

The related FMEA Worksheet (Table C.7) consists of two parts: the first part describing the potential problems and the second part describing the solutions and the timing. The first column of the Worksheet lists Part/Function/Process steps that need to be analysed in the FMEA session. This may be either the parts, the functions of the product (divided into sub-functions) or the steps in the production process. In the column of "Potential problems" all failure modes are listed (including failures in product functioning, manufacturability of the parts and assembly of the product). In the next column the cause of the potential problem is listed. There may be more causes for one problem. The effect of the problem is described in the column "Effect". By using the "Gravity Factor", the effect of the problem is also quantitatively indicated. In the column of "Solutions/Actions" proposed solutions to resolve the problems are listed or if no solutions are available actions to reduce the problems are listed. In the column of "Responsible person", a person in the project is appointed to be responsible to the problem. The last column of the worksheet indicates how far the team is with solving the problems by using the "Evolution Factor".

Table C.7 The FMEA worksheet used in the test case

No	Part / function Process step	Potential problem	Cause	Effect	Gravity factor	Solutions/ actions	Evolution factor	Responsible person

There are three types of information that are very critical to the success of using the FMEA. The first one is the information to identify the potential failure modes. The second one is the information to determine the gravity factors and the evolution factors. The third one is the information to reduce probability of occurrence. In a CFPDP, to a large extent, the three types of information are based on the information of previous products and production processes. Theoretically, the FMEA can fully predict potential reliability problems in the PDP.

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CURRICULUM VITAE

Lu Yuan was born in Sichuan, China, on 26 March 1972. In 1993 and 1995 she received her Bachelor degree and Master degree in mathematics from Xi'an JiaoTong University, China. In February 1996 she started to study for her second Master degree with the department of Industrial and Systems Engineering (ISE) at National University of Singapore (NUS). Since March 1998, she joined the Centre for Robust Design at NUS for two years, where she worked as a Research Engineer to conduct research, training workshops as well as practical projects in the field of reliability engineering and reliability management in product development processes. In February 2000 she started her doctoral work with the department of Quality of Product and Process (QPP) at Eindhoven University of Technology (TU/e). From June 2000, her PhD study has also been in the context of the joint PhD program between the NUS and TU/e.

STELLINGEN

behorende bij het proefschrift van Lu Yuan

Analysing Reliability Problems in Concurrent Fast Product Development Processes

1. Since the early 90's many articles have shown that component reliability is only one of the factors determining product reliability. At this moment most industrial product reliability metrics ignore this fact.
   Petkova, V.T., Sander, P.C., Brombacher, A.C., The use of quality metrics in service centres, International Journal of Production Economics, Vol. 67, Iss. 1, pp. 27-36, 2000; this thesis

2. Although a Concurrent Fast Product Development Process (CFPDP) has many advantages such as short time-to-market and cost effective design processes, the vulnerability of the process to effects of uncertain information is very often neglected. As a result, the efficiency losses due to poor product reliability take away more than the planned advantages.
   Rosenthal, S.R., Effective product design and development: how to cut lead time and increase customer satisfaction, Illinois: The business One Irwin, 1992; this thesis

3. Although Failure Mode and Effect Analysis (FMEA) is one of the commonly used methods to predict and manage potential failure mechanisms, it is conceptually unable to make relevant predictions when based on uncertain information.
   This thesis

4. "Garbage in and Garbage out (GIGO)" surely happens to any reliability methods if they are not well integrated in the business process.

5. In real radical PDPs, reliability prediction is unnecessary because of the highly innovative nature of the products.

6. Theoretically it is possible to apply concurrent engineering in a PhD research project, but it is very difficult to do so in practice due to the degree of innovation involved in the research process.

7. End-users with high income expect even higher product reliability, especially in the automobile industry.

8. A visit to an amusement park is very useful in understanding the nature of the roller coaster curve, especially the most troublesome Phase 1 reliability problems.

9. A joint PhD program brings you not only the joy of a joint degree but also the difficulty of a joint procedure.

10. Although giving birth to a baby is as difficult and stressful as writing a PhD thesis, a pregnancy lasts only about nine months.