# MANAGING THE UNCERTAINTY ASPECT OF RELIABILITY IN AN ITERATIVE PRODUCT DEVELOPMENT PROCESS

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# MANAGING THE UNCERTAINTY ASPECT OF RELIABILITY IN AN ITERATIVE PRODUCT DEVELOPMENT PROCESS

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# SUMMARY

This study identifies the design criteria for a method that can be used to manage the risk and uncertainty aspects of product reliability of Really New Innovations (RNI) in an Iterative Product Development Process (IPDP). It is based on 7 years of longitudinal research exploring more than 10 industrial projects and their corresponding sets of project data from the consumer electronics industry. This industry is characterized by increasing product functionality complexity, decreasing time to market (TTM), increasing globalization both in operations and development phases and reducing tolerance of customers for perceived quality issues. The traditional quality and reliability management methods focus primarily on risk management, which is not sufficient given the characteristics mentioned before.

Hence there is a need to develop RNI where the risk and especially uncertainty aspects of product reliability have to be managed. Uncertainty refers to an event where the system parameters are known but the probability of occurrence or severity of the event is unknown as there is no or limited information available.

The research findings showed that the Reliability Quality Matrix (RQM) is an effective method that helps to manage uncertainty in derivative products and that a new method needs to be developed to help manage uncertainty in RNI, especially for areas beyond the product parts and production process. Four design criteria for the new method were developed, which are proactiveness, completeness, flexibility, and information type. To demonstrate the validity of the design criteria, a new method, called RQM-Lite was developed and implemented in industrial projects. A prototype RQM-Lite tool was also developed to support the process.

The initial implementation of the RQM-Lite method in case studies showed that it helped the project team to have a more complete scope for uncertainty indication.

This is done through a top-down structured process and application of Information Granularity. Information Granularity is a process of decomposing macro elements of information into micro elements of information. As it is not possible to obtain or process all of the detailed information in the early phases of the IPDP, the concept of resolution is adapted and applied to information so that we have a new dimension called Information Resolution. This concept is used to achieve an “acceptable level of uncertainty, hence risk” to make satisficing decisions in the early phases of the IPDP. In other words, low resolution information is used to make a relative indication of the uncertainty in the RQM-Lite method rather than use only high resolution information for an absolute value.

This thesis has shown how the RQM-Lite method is used to identify uncertainties proactively. By applying a top-down approach and the concept of information granularity, the required low and high resolution information can be gathered for uncertainty analysis, assessment and management. Through iterations, the information gaps can be reduced resulting in lower uncertainty. Once the required information is obtained to make an estimate of the underlying probability of occurrence, risk analysis, assessments and management can be carried out using the existing development and quality tools.

The design criteria that have been developed and the prototype RQM-Lite method used to validate the criteria, when compared to the available alternatives and despite the limitations of this research, shows promise and provides more objectivity, especially in the field of uncertainty management of product reliability for RNI in IPDP.

# SAMENVATTING

De huidige combinatie van influx van nieuwe technologie, de resulterende druk op time-to-market en een toenemende dynamiek in de businessketen leidt tot een toenemende aandacht voor "product en project risico's". Dit onderzoek identificeert ontwerp criteria die gebruikt kunnen worden voor het beheersen van aspecten van risico en onzekerheid van de product kwaliteit van radicaal nieuwe, innovatieve producten in een iteratief product ontwikkel proces (IPOP). De studie is gebaseerd op 7 jaar longitudinaal onderzoek in meer dan 10 industriële projecten en de onderliggende project data in de sector consumenten elektronica. De traditionele kwaliteits- en bedrijfszekerheid management methodes focusseren voornamelijk op risico management, wat blijkens dit onderzoek niet voldoende blijkt te zijn in de industriële situatie die hierboven geschetst is.

Om deze redenen is er een behoefte om de risico en onzekerheid aspecten bij het ontwikkelen van radicaal nieuwe, innovatieve producten beter te beheersen. Hierbij refereert onzekerheid aan gebeurtenissen waarbij de systeem parameters bekend zijn, maar waar voor de kans van optreden en/of de gevolgen van de gebeurtenis geen of beperkte informatie aanwezig is.

Voorgaand onderzoek heeft aangetoond dat de ‘Reliability Quality Matrix’ (RQM) een effectieve methode is om onzekerheid te beheersen bij het ontwikkelen van afgeleide producten en dat een nieuwe methode ontwikkeld moet worden voor beheersing van onzekerheid bij radicaal nieuwe producten, in het bijzonder voor de fases buiten het daadwerkelijke vervaardigingsproces. Vier ontwerpcriteria zijn ontwikkeld voor de nieuwe methode: proactiviteit, compleetheid, flexibiliteit en informatie type. Om de validiteit van de criteria te demonstreren is een nieuwe methode genaamd RQM-Lite ontwikkeld en geïmplementeerd in industriële projecten. Een prototype van een RQM-Lite tool is ontwikkeld om het proces te ondersteunen.

De initiële implementatie van RQM-Lite in case studies liet zien dat het hielp om het project team een beter en completer overzicht te geven van de verschillende aspecten van onzekerheid. Hierbij is, via een top-down proces, met name gekeken naar de ‘Information granularity’. Information granularity is een proces om macro informatie op een eenduidige wijze te relateren naar elementen op micro niveau. Omdat het niet mogelijk is om alle detail informatie in de vroege fases van het IPOP te verkrijgen of te verwerken, is het nieuwe concept ‘Information Resolution’ (unieke identificatie van verschillende niveaus van resolutie) hiervoor ontworpen. Met behulp van dit nieuwe attribuut is het mogelijk geworden om in RQM-Lite gebruik te maken van een relatieve indicatie van onzekerheid in plaats van de traditionele absolute waarde met de daaraan verbonden nauwkeurigheidseisen.

Dit proefschrift heeft aangetoond hoe RQM-Lite gebruikt kan worden om onzekerheid proactief te identificeren. Door een top-down aanpak en gebruik makend van ‘information granularity’ kan de benodigde hoge en lage resolutie informatie verzameld en gebruikt worden voor analyse, beoordeling van en management van onzekerheid. Door middel van iteraties kan missende informatie aangevuld worden resulterend in verminderde onzekerheid. Als de benodigde informatie verkregen is, kan een schatting worden gemaakt van de kans op voorkomen, waardoor risico analyse en management uitgevoerd kan worden met de bestaande ontwikkelings- and kwaliteitsmethodes.

Ondanks de beperkingen van dit onderzoek blijken het ontwikkelde ontwerp criteria, de RQM-Lite methode en het prototype gebruikt om de criteria te valideren zinvol en meer objectief te zijn in de toepassing voor onzekerheidsmanagement voor radicaal nieuwe producten in een IPOP vergeleken met de bestaande alternatieven.

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# CHAPTER 1 INTRODUCTION

Technology is evolving at a fast pace [Cooper, 2000; Segerstrom, 2007]. New products with increased functionality and technology are introduced into the market at an ever faster rate and consequently the economical product life cycles get shorter [Minderhoud and Fraser, 2005]. This is clearly demonstrated by the life cycles of three different products. It took about 30 years for Video Cassette Recorders' (VCR) to become a commodity, 5-6 years for Digital Versatile Disc (DVD) Players and about 3 years for Digital Versatile Disc Recorder (DVD-R) products [Minderhoud and Fraser, 2005]. Obviously the time between product introductions is getting shorter which puts a tremendous pressure on the Time to Market (TTM).

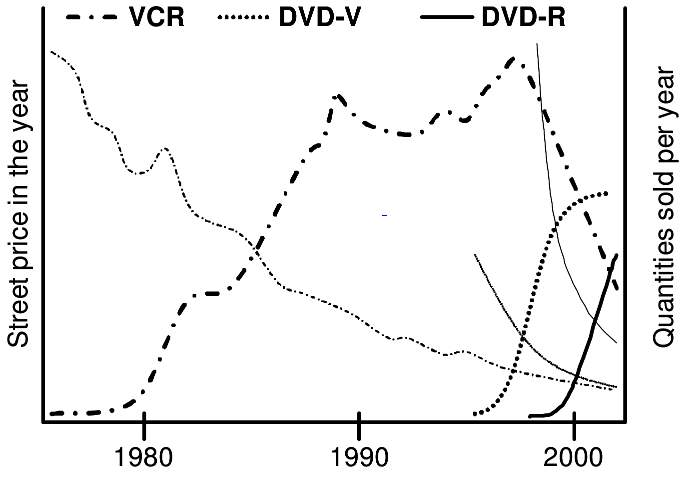

*Figure 1-1: Market Dynamics for Three Types of Consumer Electronic Products [Minderhoud and Fraser, 2005]*

Minderhoud [1999] mentioned that many mistakes happen when skipping important steps, which affects the information gathering process, for example, reducing TTM was achieved through removing or reducing safety mechanisms such as product quality and reliability (Q&R) tests. This thesis aims to explore how manufacturers can manage a high product Q&R in such a situation.

The research framework is defined in section 1.1 and the problem statement, research questions and research objective are formulated in section 1.2. In section 1.3 the research methodology is discussed. As this research is multi-disciplinary in nature and as different disciplines often use the same words with different connotation, a list of relevant definitions as used in this thesis is provided in section 1.4 and the outline of the rest of this thesis is given in the last section.

## 1.1. Research Framework

Current product development processes in the innovative consumer electronic industry has four characteristics that have major implications for the way in which reliability should be managed. These characteristics are:

- Increased product complexity [Goldhar et al., 1991; Minderhoud, 1999]
- More outsourcing & globalisation [den Ouden, 2006]
- Need for a short Time-to-Market (TTM) [Chapman and Hyland, 2004; Wheelwright and Clark, 1992; Minderhoud and Fraser, 2005]
- Decreased tolerance of consumers for quality problems [Babbar, et. al, 2002; Brombacher, 2005]
-

These conflicting characteristics create a very demanding product development situation; products have to be developed in ever-shorter development cycles in an environment where the products get more complex, more parties are involved and higher Quality and Reliability (Q&R) standards are required.

The type of innovation required to develop these complex products is defined by [Garcia and Calantone, 2001] in terms of the level of marketing and technological discontinuity as well as a macro-level and micro-level perspective. Radical innovations will result in a product that has both market and technological discontinuity at the macro level while a Really New Innovation (RNI) product will have either a marketing or technological macro level discontinuity, in combination with a micro level discontinuity. As RNIs comprise the majority of innovations [Garcia and Calantone, 2001], this will be the area of interest for this research.

In order to deal with time pressure, a Product Development Process (PDP) requires a very high predictability [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 iterative PDPs vs. iterative reliability management. This thesis is especially interested on the RNI in an iterative PDP (IPDP).

In the area of Q&R standards, the traditional Q&R management focus on risk management, and the need to proactively manage risk in Product Development Process (PDP) has been well recognized [McCormack, 2001; Verganti, 1997; Minderhoud, 1999]. However, [denOuden, 2006] has shown that these Q&R management approaches as they are applied during the design of products are not enough to meet the customers' expectations. As a result, there is an increasing trend in customer complaints for new innovations in the consumer electronics industry.

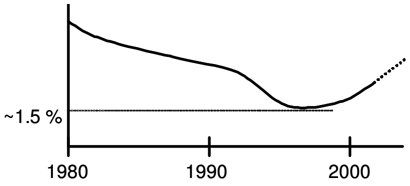

*Figure 1.2 - Average % of consumer complaints on new products[den Ouden, 2006]*

Recent research showed that in addition to the risk metric, the uncertainty parameter must not be ignored in this process [Claycomb et al., 2002; Gil-Aluja, 2001; Verganti, 1997; Minderhoud, 1999; Lu, 2002]. In common language, these two terms are often used as synonyms; however there is a significant and fundamental difference between the two terms. A detailed review of the difference will be done in chapter 2.

The way uncertainties should be dealt with differs from the way risks should be dealt with [Lu, 2002]. This thesis will demonstrate how to manage uncertainties. Risks cannot all be identified at the start of a project because of the uncertainties arising from missing or unknown information. The need for proactive reliability management focusing on risks and uncertainties has been clearly identified by [Lu, 2002]. Lu's research focused on analysing the causes of reliability problems in concurrent fast product development processes (CFPDP). She developed the Reliability and Quality Matrix (RQM) method with supporting tool to handle reliability information flows in CFPDP which have a high degree of uncertainty.

As this research is interested in Really New Innovations (RNI) in an Iterative PDP (IPDP), it is thus a direct follow-up research to the one done by [Lu, 2002][1]. This thesis will extend the scope of her research and find out how to manage reliability, especially the uncertainty aspect, of RNI in an IPDP. More detailed analysis of the research on the innovation classification, type of PDPs, risk and uncertainty will be presented in chapter 2.

*Research problem: How to manage reliability of really new innovations, especially the risk and uncertainty aspects in iterative product development process*

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[1] Analysing Reliability Problems in Concurrent Fast Product Development Processes (ARP-CFPDP)

## 1.2. Problem Statement, Research Questions and Research Objective

It has been shown above that there is a need to proactively manage reliability of RNI in an iterative PDP, which includes the metrics of risk and uncertainty. The prior research of [Lu, 2002] developed the RQM method to manage uncertainties in CFPDP. Based on 7 years of longitudinal research exploring more than 10 industrial projects and their corresponding sets of project data, it was found that the RQM method worked very well in CFPDP that had a high degree of uncertainty. However, due to the four characteristics mentioned above that result in RNI being developed in an IPDP, the related research proposition is identified as follows:

*Research proposition: Since RQM can be used to manage the uncertainty aspect of reliability information flows in CFPDP, it can similarly be used for RNI in IPDP.*

In chapter 2, a detailed review of the various product innovations and the types of product development process will be discussed. For now, it will be summarised that RNI have more uncertainties associated with the reliability information due to the gaps in the required information as they are more innovative than derivative products. Though RQM is effective for uncertainty management of derivative products in a CFPDP, it will be necessary to establish the effectiveness of RQM for uncertainty management of really new innovations that are developed in an IPDP. This leads to the research questions of the thesis.

*Research question 1: How effectively can risk and uncertainty aspects of reliability be managed for RNI developed in IPDP using the RQM method?*

If the RQM method is found to be effective, it is necessary to identify what design criteria resulted in the effectiveness so that further improvements can be made. On the other hand, if the RQM method is ineffective, the new design criteria for a framework to manage the reliability of RNI in IPDP will need to be developed.

*Research question 2: What are the design criteria that can be used to manage risk and uncertainty aspects of reliability of RNI being developed in IPDP?*

Therefore, by identifying these design criteria, it should serve as the basis for developing a broader and more comprehensive method that can help achieve the research objective.

*Research Objective: To identify the design criteria for a method that can be used to manage reliability, especially the risk and uncertainty aspects, of RNI in an IPDP.*

## 1.3. Research Methodology

The research described in this thesis is classified as design-oriented applied research since this research aims at developing the criteria for a method to manage reliability of RNI in IPDP. The research results will be presented in the form of design knowledge. According to [van 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 [van Aken, 1999]. Together they describe what should be done in order to attain a desired situation.

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 intends to find out how to manage reliability, which includes the risk and uncertainty aspects, of RNI in IPDP. Case study approach was used in this thesis to identify the research problem, to analyse the research problem and to carry out a first implementation of the proposed design criteria.

The regulative cycle for research activities can be broken into problem identification, diagnosis, design, intervention and evaluation [van Aken, 1999]. In this research, the relevant literature was studied, practical observations were made and discussions with experts were held. Four main stages corresponding to the five steps can be distinguished in this research and is outlined below.

| Research Steps | Contents of Research Stage |
|---|---|
| 1. Problem Identification | The relevant literature was studied, archived records from the product development company on their projects and historical case study was used to identify the research problem, research questions and research objective. |
| 2. Diagnosis | A case study approach was used to find out how effective is the RQM method to help manage reliability of RNI in IPDP.<br>Analysing the causes of effective / ineffective management of reliability |
| 3. Design | A second round of literature review to develop the design criteria to manage the uncertainty of RNI<br>Identify the formal requirements and translating the formal requirements into a reliability management method. |
| 4. Intervention<br>5. Validation | Carry out a first implementation of the method through industrial case studies and reflect upon the findings. |

As we are dealing with case studies that typically require more than two years for full customer feedback and have many factors that are adapted as the organisation learns from experiences in the real environment, the multiple case study validation [Yin, 1994] is adapted by selecting cases which are general to the industry and not specific to the company. Furthermore, the dynamic and evolving nature of PDP makes it impractical to freeze or isolate all the external variables. An embedded multiple case study design approach, where the distinct sub-units inside the case study will be studied and the design solution will be reapplied to the past case studies in addition to the new case studies. This increases the so called replication in order to strengthen the generalization and overall validation of the research. If all the signs point to the same direction, then the conclusions from these case studies and overall research will be scientifically sound.

## 1.4. Relevant Definitions

A number of important definitions used in this thesis are listed in the table 1.1 below. These definitions are quoted in this thesis when necessary. Some of these definitions may have different meanings if they are viewed outside this thesis; however, they are adjusted to be applicable within the scope of this thesis.

*Table 1-1: Relevant Definitions*

| Terminology | Definitions |
|---|---|
| Business-to-business | Non-consumer purchasers such as manufacturers, resellers (distributors, wholesalers and retailers, for example) institutional, professional and governmental organizations, frequently referred to as ‘industrial’ businesses in the past [PDMA, 2004] |
| CFPDP | Concurrent fast product development process is one that optimise reliability early in concurrent PDPs, which enables the following process to run simultaneously and eventually more smoothly and faster [Lu, 2002] |
| Consumer | Refers to current customers, competitors’ customers, current non-purchasers with similar needs or demographic characteristics. The term does not differentiate whether a person is a buyer or a user target |
| 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 |
| Failure Modes and Effects | A technique for enumerating the possible failure modes by which components may fail and for tracing through the |

| | |
|---|---|
| Analysis (FMEA) | 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, 2004] |
| 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]) |
| Innovation | Is an iterative process initiated by the perception of a new market and /or service opportunity for a technology based invention which leads to development, production and marketings tasks striving for commercial success of the invention. [Garcia and Calantone, 2002] |
| IPDP | An iterative PDP or dynamic PDP [Yazdani and Holmes, 1999] is one where customers are involved right from the beginning, many decisions are initiated and much iteration takes place in early phase. |
| Known technologies | Technologies are considered to be known to the organization if they have been applied under comparable circumstances before in the organisation |
| PDP | Product Development Process : 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 |
| 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, 2004] |
| Quality | The total features and characteristics of a product or service that bear on its ability to satisfy given needs [Lewis, 1996] |
| 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, 2004] |

| | |
|---|---|
| Quality of information | Correctness, Completeness, Up-to-date, Verifiable, Accuracy, (selection, detail level) [Bemelmans, 1991] |
| 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] |
| Risk | Risk as a concept reflects the probability of occurrence of a potential failure together with its severity and solvability [Williams, 1993]. If one is unable to identify the events that cause and drive the risk, then there is uncertainty. |
| TTM | Time-to-market: 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, 2004] |
| Uncertainty | • Uncertainty about a situation exists when one does not understand a situation well enough to explain how the situation came to be or to predict what will happen next in that situation [Sanchez and Heene, 2004]. The definitions as used in this research are as follows<br>• Analysis Uncertainty – refers to event where the system parameters are known but the probability of occurrence or severity of the event is unknown as there is no information available<br>• Type 1 Lu Uncertainty – refers to an event where the system parameters are known but the probability of occurrence or severity of the event is unknown even though there is information available. This information is either not available to the developer or was not used<br>• Type 2 Lu Uncertainty – refers to an event where the system parameters are known but the probability of occurrence or severity of the event is perceived to be known as there is gap between the required and available information in terms of level and quality |
| Unknown technologies | Technologies are considered to be unknown to the organization if they have not been used before |

## 1.5. Outline of the Thesis

The organisation of this thesis is discussed here. In Chapter 2 the results of the literature review aimed at identifying methods that can be used to manage the risk and uncertainty aspects of reliability of RNI in IPDP is presented. The review covers the types of innovations and PDPs, concept of risk and uncertainty for reliability management and available approaches to manage these risks and uncertainty. Chapter 3 presents industrial case studies conducted in a multinational company in order to answer the first research question and to identify the causal factors for the effectiveness of RQM. Based on this, the concepts and design criteria for proposed method to manage the risk and uncertainty in IPDP is presented in chapter 4.

In Chapter 5, a prototype method for managing risk and uncertainty in IPDP is developed and is applied in industrial cases in chapter 6 to demonstrate the applicability of design criteria. The results of the first implementation are then reflected upon in the context of the research objective.

Finally in chapter 7, the research findings are summarised, evaluated and the contributions are highlighted. To conclude, the limitations of the research are presented and recommendations for future research directions are proposed.

# CHAPTER 2 UNCERTAINTY MANAGEMENT OF PRODUCT RELIABILITY

This research project is interested in how effectively the uncertainty and risk aspects of product reliability are managed by RQM for RNI developed in IPDP. Therefore, it is necessary to conduct a literature review in order to understand the recent development in the related areas. Firstly, it is important to understand the characteristics of the consumer electronics industry where this project is conducted. Secondly, uncertainty as a relevant aspect in product reliability for consumer electronics products under time pressure is discussed. Next, a thorough understanding of the uncertainty and risk aspects of the product reliability and the approaches that are currently available on identifying and managing uncertainty and risks is required. It is also essential to understand whether the approaches for uncertainty and risk analysis, assessment and management could be applied to the different types of product innovations as well as product development processes.

This chapter is organised as the follows. The characteristics of the consumer electronics industry are covered in section 2.1 with a short overview of product reliability in section 2.2 which highlights the areas for uncertainty management. In section 2.3, a detailed review on risk and uncertainty in literature shows what approaches are currently available. Section 2.4 and 2.5 reviews the different types of innovations and product development processes respectively. Conclusion is given in Section 2.6 that leads to the research proposition.

## 2.1. Industry Characteristics

The reliability of technical systems in the consumer electronics industry is currently affected by the following four major industry characteristics [Brombacher, 2005]

- Increased product complexity
- More global economy
- Need for a short Time-to-Market (TTM)
- Decreased tolerance of consumers for quality problems
-

These characteristics correlate strongly with the context as seen in this research. In this section, the characteristics are described from the perspective of the consumer electronics industry and will lead to the focus of this research.

### a. Increased product complexity

Technological innovation is taking place at a faster pace [Birnbaum, 1998; Cooper, 2000; Segerstrom, 2007]. Increasing complexity in technologies naturally contribute to the increasing complexity and diversity in products [Minderhoud, 1999; Goldhar et al., 1991]. Many products are not developed to perform a single function, like the black & white television (TV) that is just meant to display a TV signal or a traditional handphone that is meant for voice communications. The current models of these products are multi-functional and in many cases need to operate in a network of different products. Some of the latest TV models have a built in hard disk, new audio & video features and interconnectivity with various cable receivers, home cinema sets, DVD recorders, digital cameras and multimedia PCs. Similarly the latest handphones have features similar to Personal Digital Assistants (PDA), digital camera, MP3 player, tuner function and provide web access, multimedia & business applications.

Analysing the quality and reliability problems becomes more complex due to increasing features, interoperability and connectivity issues. [Brombacher, et.al.,2005b] finds an increasing amount of complaints in the service centres where the cause of complaint cannot be established. Regardless of the reason behind this phenomenon, it is necessary to identify the root cause of these consumer complaints so that the increasing complexity can be managed in order to deliver required products. One of the ways to manage the increasing complexity is to leverage on external expertise through outsourcing [Harland, et. al, 2003].

### b. More global economy

Outsourcing involves the use of specialists to provide competence, technologies and resources to provide parts of the whole. Increased outsourcing allows access to global markets, and may cause organisations to seek international sources for perceived ‘best in class’ performance [Harland, et. al, 2003]. The current wave of outsourcing is motivated by this desire to innovate ahead of competition. This outsourcing phenomenon is the start of a new pattern of innovation in the way we manage. The ability to fragment complex management processes and reintegrate them into the whole is a new capability [Prahalad, 2005].

The increasingly complex business process where value chains are disintegrated due to globalisation and development activities are outsourced puts increasing demands on the quality and reliability information flows [den Ouden, 2006]. Information from the source location now not only needs to be communicated to the various disciplines within the company but also to other locations in different parts of the world and therefore to very different cultures and information systems. This is further compounded if more parts of the business chain are outsourced to 3rd party. The complexity of information networks increases and impacts the data integrity, speed and quality of information [den Ouden, 2006]. This becomes critical for new products or technologies that rely on this information, especially when standards are not (yet) available.

### c. Need for a shorter time-to-market (TTM)

In the last fifteen to twenty years, companies have experienced considerable pressure to improve both the quality and speed of product innovation [Chapman and Hyland, 2004]. Time based strategy is a competitive strategy that seeks to shorten the time taken to develop and launch a product [Stalk, 1988]. In a first mover strategy, firms that reach the market first achieve higher average profit and market share [Kerin, et. al., 1992] while in an alternative fast follower strategy, firms recognize the risks of being first. In the first situation, developing and launching the product late in the market results in competition from products with increased functionalities at the same price or cheaper products with the same functionalities. From a cost perspective, the importance of a short TTM is illustrated in figure 2.1 which demonstrates that TTM is one of the main profit drivers. In the latter situation, some companies may not want to invest in the huge development costs associated with being a first mover. They wait until a competitor launches a product, then imitate and improve upon it. However, in both strategies, a faster TTM gives a greater competitive edge over later entrants [Kessler and Chakrabarti, 1996]. Furthermore, TTM differentiates the firm from its competition through faster learning and greater proliferation of products into the marketplace [Wheelwright and Clark, 1992].

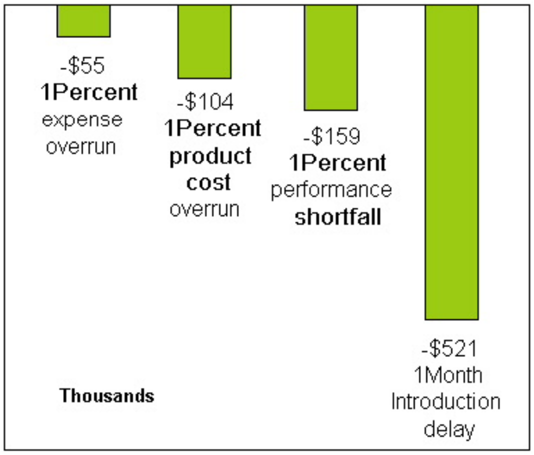

*Figure 2.1: Profit Importance of TTM Compared to Three other Scenarios [Smith, 1998]*

On the other hand, learning from the field for second generation products is hampered [Brombacher, 2000] because the field feedback of the previous generation is not even available before the product concept is to be released. For the consumer electronics products, where the development time ranges between 6 to 9 months and the feedback time is a little over a 1 year, the feedback on the $1^{st}$ generation is only available when the $3^{rd}$ generation is already under development [Brombacher, et.al.,2005b]. The TTM pressure also results in the first generation products being developed with less time available for quality and reliability management [Minderhoud and Fraser, 2005].

All of the above puts extra pressure on the product development process within the company and on the reliability management of the products because less time is available to develop highly reliable products that meet the customers' expectation.

### d. Decreased tolerance of consumers for quality problems

[Goldhar, 1991] describes how customers are becoming increasingly more sophisticated and are demanding customised products more closely targeted to their needs. In parallel, the consumers' tolerance for quality and reliability problems with products is decreasing. In other words, their understanding of what can go wrong with the product or systems is declining. To elaborate, people use and accept products provided to them but do not understand (and therefore) do not accept the underlying complexity of the product. The more user-friendly the design of a product, the better is the consumers' experience with the product [Babbar, 2005]. Usability is a critical aspect of product design [March, 1994].

[Babbar, et. al. 2002] have mapped out the different dimensions of product usability that were found to cause customer dissatisfaction. These include 'product does not provide sufficient information for use', 'product does not provide customer with sufficient control', 'product needs to be constantly reset', 'product components are incompatible', 'product has missing feature', 'product has dysfunctional feature', 'product falls apart shortly' and 'product difficult to access (during unpacking, use or service)'. Having a product that meets all these requirements the moment it leaves that factory is not enough, that is quality alone is not enough, the product has to be reliable also. Customers expect it function similarly over a specific period of time [Lu, 2002]. This is resulting in companies extending warranty periods and also widening the scope of the warranty. Consumers are allowed to return products for 'hard failures' (product not meeting specification) and 'soft failures' (product meets technical specification but does not meet the consumers' expectations) [Berden, et. al., 1999]. In the remainder of this thesis, the term consumer requirements shall be used to refer to both the consumers' requirements for the technical specification to be met as well as the reduction of the consumers' dissatisfaction.

The above four characteristics lead a challenging product development environment. This research is thus interested to find out how innovative products with required reliability which meets the increased customer requirements can be developed.

## 2.2. Product Reliability

Reliability is defined by [Lewis, 1996] as the probability that a system will perform its intended function for a specific period of time under a given set of conditions.

The bathtub shaped curve is used to model the different phases of failure rate [Lewis, 1996] by classifying the product failures into three groups, namely infant mortality, random failures and wearout. Though the model is criticised by researchers, it is popular in the industry because it greatly simplifies the mathematics involved and is easy to implement. 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. 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. This is the reason why many industries use the constant failure rate approximation, i.e. the exponential distribution, to describe the reliability behaviours of their components even though their products may exhibit moderate early failures as well as/or aging effects.

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]. [Lu et. al, 2000] reported that reliability problems from early phases of the roller coaster curve were found to be more critical especially under the increasing TTM pressure. These problems were found mainly due to the fuzziness that exists in the product reliability information [Lu, et.al, 2001]. In other words, the available reliability information does not have the required quality level or the deployment level (from customer, to service centre, to the factory, to the development team, to the supplier and /or within the company). Fuzziness is used to describe the level of uncertainty associated with the risks due to imperfect knowledge or information in risk management [Jablonowski, 1995]. This research is thus interested in product reliability due to uncertainty in product reliability information. To understand uncertainty in information, it is necessary to conduct literatures review on not only uncertainty but also on risk because these two concepts are closely related but still very different [Wynn, 1992; Lu, 2002].

## 2.3. Risk and Uncertainty

The management of risk has become the subject of growing concern to individuals, organisations and society at large [Ansell and Wharton, 1992]. As per the concise Oxford Dictionary (1976), risk refers to '….the chance of hazard, bad consequence, loss, etc…".

In the more scientific and specialized literature, risk is used to imply a measurement of the chance of an outcome, the size of the outcome or a combination of both. Though it is convenient to incorporate both in one definition, [Williams, 1996] contends that multiplying the likelihood of risk and the consequence of risk is misleading. A trivial example to illustrate this point is that a 0.001 probability of losing $1000 is not the same as 0.1 probability of losing $10, though these two risks would be seen as "equivalent" in a ranking of probability (or likelihood) multiplied by impact (or consequence) even if their effect is quite different. This need to treat risks in both dimensions is extended by [Charette, 1989] into a 3 dimensional graph with independent axes that he labels as severity (i.e. impact), frequency (i.e. likelihood) and 'predictability' (i.e. extent to which the risk is aleatoric rather than epistemic). Aleatoric probability refers to the outcome of an intrinsically uncertain situation and epistemic probability relates to a measure in belief in a proposition, or more generally to a lack of complete knowledge. [Wynn, 1992] takes this distinction further by distinguishing between

- Risk – where the 'odds' are known
- Uncertainty – where the 'odds' are not known, but the main parameters may be
- Ignorance – where we don't know what we don't know
- Indeterminacy – described as 'causal chains', presumably implying an element of unknowability

According to [Wynn, 1992] Risk is when the system of behaviour is basically well known, and the likelihood of different outcomes can be defined and quantified by structured analysis of mechanisms and probabilities. If we know the system parameters (i.e. know of their existence) but cannot calculate the probabilities of occurrence, then we refer to it as uncertainties. An illustration of the first two definitions with an example follows. An investor, who has put his money in treasury bills until maturity, can calculate with certainty the exact amount of interest he will receive. If the same investor flips a coin to make a decision, he is taking a risk, in that he knows what the outcomes are, as well as their probabilities, though he cannot be certain which outcome will occur. If the investor were to buy a particular stock on any Stock Exchange, the stock price on the next day may go up, down or remain unchanged. There is uncertainty as to the outcome as there is no way of knowing the exact probability of any of the three outcomes. These two definitions are the most relevant to the management of product reliability information related to failures from the early phases of RNI development in the consumer electronics industry. The first is obvious while the second is due to the limited availability of historical evidence on which to base the predictions. Failures due to ignorance or indeterminacy are not covered as it is beyond the scope of this research, which focuses on products whose life cycles are short and where any design changes (if significant and necessary) can be introduced in subsequent product models.

Before we review the techniques for risk analysis, assessment or management, it should be acknowledged from the trivial example at the beginning of this section, that the risks at issue are perceived risks and not necessarily actual risks. Individuals and organizations make decisions based on perceptions about the likely consequences of their actions [Wharton, 1992]. Any responsible decision maker will make every effort to obtain a complete and accurate perception of the risks faced before attempting to undertake an analysis or assessment. The identification of possible outcomes of decision is the purpose of risk analysis whilst the estimation of probabilities and the size of the outcomes is the subject of risk assessment.

Similarly, the purpose of uncertainty analysis is the identification of system parameters or their existence and the result is an indication of the 'analysis uncertainty' for the possible outcome. From empirical studies [Lu, 2002] has found that 'analysis uncertainty' may occur even if the information required to make the analysis and assessment is available in the organisation. The situation arises because the available information is not available to the people making the analysis or assessment and it is termed as 'Type 1 Lu Uncertainty' in this research.

This concept of not using available information for uncertainty analysis can be extended to cover the situation described by [Jackson and Carter, 1992] which will be explained through an example. For a situation where a 100 aircraft are about to depart, it has been computed that each plane has a 99% chance of arriving safely, however in practice each plane will either arrive safely or it will not. The individual ratio in such a situation has no sensible meaning. If 99 aircraft arrive safely and 1 crashes, then for the 99 safe arrivals the prediction is too pessimistic but for the 1 crash it is too optimistic. For a passenger considering a flight in one of those planes, the significant consideration is not the probability but whether it will arrive safely. Whereas probability will deal with the likelihood of the occurrence of an event within a population, possibility focuses on particular events. If a system failure is utterly unpredictable, perhaps due to absence of technology to predict it, clearly little can be done to minimize the risk. But in most cases of system failure, such failure could and ought to have been predicted. To give a simplistic example, assume the 1 plane crash was found to be a result of insufficient fuel which could have been easily predicted. The passengers concern then would be, not the probability of the plane departing without enough fuel, but the possibility that it can do so. This situation where the information required to predict the failure exists but is not used will also be considered as part of 'Type 1 Lu Uncertainty' in this research.

Uncertainty assessment by definition is not possible as an estimate of the probability or the size of the outcome is unknown. However, [Lu, 2002] has pointed that if an assessment is done on identified system parameters using perceived complete information, but in reality there is a gap between the required information and the available information, it may give rise to an uncertain estimation of probabilities and the size of the outcomes. This is termed as 'Type 2 Lu Uncertainty' in this research. The various terms for risk and uncertainty as used in this research and what they mean are shown below.

- Risk – refers to an event (which is more aleatoric) where the probability of occurrence and the severity is known
- Analysis Uncertainty – refers to event where the system parameters are known but the probability of occurrence or severity of the event is unknown as there is no information available
- Type 1 Lu Uncertainty – refers to an event where the system parameters are known but the probability of occurrence or severity of the event is unknown even though there is information available. This information is either not available to the developer or was not used
- Type 2 Lu Uncertainty – refers to an event where the system parameters are known but the probability of occurrence or severity of the event is perceived to be known as there is gap between the required and available information in terms of level and quality

### 2.3.1. Risk Analysis and Assessment

According to the Concise Oxford Dictionary, 1976, analysis is the separation of a whole into its component parts: an examination of a complex, its elements and their relationship. [Maccrimmon and Wehrung, 1986] represent the basic risk paradigm in the form of a decision tree as illustrated in Figure 2.2,

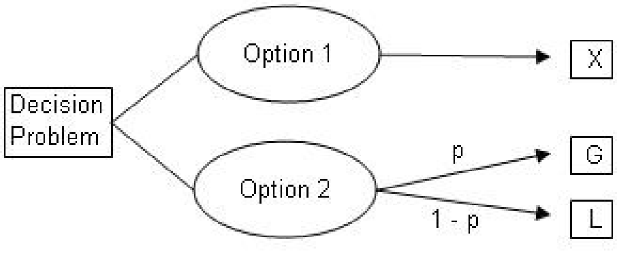

*Figure 2.2: The basic risk paradigm*

In a decision problem, there is a choice between just two options, one which will have only one possible outcome whilst the other option (2) has two possible outcomes. Option 1 leads to a certain outcome (there is often no change to or status quo), and the option 2 has two probabilistic outcomes, one being a gain and the other a loss. Two simple examples of the basic problem would include the decision by an investor as to whether to leave his savings in a secure bank account or to invest them in a new share issue; the decision by a manufacturer to continue to market the existing product or to replace it with a newly developed product. In these examples, the possibility of gain is accompanied by the risk of loss. Although actual decision problems may have many more options and outcomes, the structure illustrated above has the essential elements. Extensions and variations to the basic structure might include the possibility of a sequence of connected decisions, several options or a continuum of possible outcomes for some options [French, 1986; Moore and Thomas, 1976] as would be the case in product development project. At each decision point, however, the essence of the problem is the same, the need to compare two or more options with probabilistic outcomes. The process of estimating the probability and size of outcomes, and then evaluating the alternative courses of action is one of risk assessment.

Risk assessment, the evaluation and comparison of risks, from an economic perspective, is often assumed to be some form of cost-benefit analysis. It is generally assumed that if more information were available, then accidents (or risk) would be avoided through rational action, however this may be an unattainable goal [Jackson and Carter, 1992]. This is due to the situation where the amount of data required for making a rational choice may be overwhelming [Shapira, 1994]. Several principles were developed to help simplify such decision making situations, prominent among them being [Simon, 1976]'s satisficing principle. According to this model, in simplifying choice problems, decision makers consider alternatives in only a subset of the entire set of alternatives. They then select the best alternative from this subset of the entire set, thus the process does not necessarily end up with the optimal alternative being chosen but a good enough alternative within the practical constraints.

If statistical concepts are applied, then one of the ways is to include a statistical measure of dispersion or variability as a measure of risk and then calculating the expected value. However, in practice this concept of using statistics has numerous limitations, not the least of which stems from the fact that most decisions or actions are taken in situations which do not repeat themselves [Wharton, 1992]. As an example, an analysis of a problem in a manufacturing process can be done with statistical models as there are many repetitions unlike in new product development where there may be one or two repetitions, and even then, the information may not be available to the public as it is confidential. Hence in this research, risk assessment using statistical concepts will be used but its applicability may be limited.

The other aspect would be the psychological aspect where the decision making behaviour is frequently situation dependant, in which human beings perform in a manner determined by their limited memory, retention and information processing capabilities. Literature review on this aspect shows that risk behaviour are directly influenced by roles of problem framing [Kahneman & Taversky, 1979], cultural risk values [Douglas & Wilavsky, 1982], leadership [Schein, et. al., 1980], group homogeneity [Janis, 1972], problem familiarity [Slovic, et. al., 1980] and risk preferences [Brockhaus, 1980]. [Sitkin and Pablo, 1992] have hypothesized that these factors that were previously considered to have direct influence on risk behaviour, to have an influence instead on risk perception and risk propensity. In addition they have proposed that inertia and outcome history to be included as additional influences on risk propensity. The second addition is that organizational control systems and risk propensity to be considered as additional determinants of risk perception. From a political aspect, a decision maker may be influenced by considerations of who is to be affected by each particular outcome. [Rescher, 1983] points out that in many situations, risk assessment is very much subject to consideration of moral and ethical values in which a fundamental principle is that whilst an individual may take a calculated risk on his own account, he must proceed more conservatively where the interests of others are at stake. As it is beyond the scope of this research to study the effects of each and every theory above on the risk assessment for product reliability, all of these factors will be considered in general terms as the human factors that affect risk assessment.

Risk analysis and assessment allows a design to be evaluated and provides a framework within which alternative modifications can be proposed and quantitatively compared. However, it is important to appreciate the limitations of quantitative information. Frequently there will be uncertainty in such information concerning the physical processes, product technology, equipment reliability, human factors, incomplete information, etc. This uncertainty is not created by risk analysis but is a reflection of the state of our engineering knowledge.

### 2.3.2. Uncertainty Analysis and Assessment

Failures to cope with uncertainty in the management of technological risk abound [Wharton, 1992]. Their causes include overconfidence in scientific knowledge, the underestimation of the probability or consequences of failure, not allowing for the possibility of human error and plain irresponsibility concerning the potential risk to others.

Uncertainty analysis serves to highlight uncertainties so that their effect can be appreciated rather than hidden in superficially exact rules or judgement. [Sanchez and Heene, 2004] describes uncertainty as follows: “Uncertainty about a situation exists when one does not understand a situation well enough to explain how the situation came to be or to predict what will happen next in that situation.” This implies that the uncertainty arises from a gap between the required information and the available information. [Lu, 2002] has developed the Reliability Quality Matrix (RQM) process which helps to identify these gaps in information and thus carry out the uncertainty analysis and assessment. A detailed explanation of this process is found in the appendix. In brief, the process consists of 7 major steps. Table 2.1 describes its structure and this is followed by an explanation of relevant steps and how they aid in the risk and uncertainty analysis and assessment.

*Table 2.1 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 project, product and process related reliability problems |
| Step 6 | Predict failure probability for both known and unknown production process steps and product parts |
| Step 7 | Predict reliability performance in the factory and at customer sites |

In step 3, the production process step and the product parts are listed. Each of these is a decision problem or event. In step 4, the risk and uncertainty analysis is done by indicating whether each of the decision events (that is the changes in the product parts or process steps) is known or unknown based on the availability of information to the developer. The known events will make up the list of risk events while the unknown events will make up the uncertain events (this is due to analysis uncertainty or Type 1 Lu uncertainty).

In Step 5, the risk and uncertainty assessment is carried out by identifying the impact of the potential reliability problems of each decision event in qualitatively terms (by assigning a “High” or “Low” to the event). Next step, quantitative information in terms of the probability of occurrence (failure probability) of the potential reliability problems related to each decision event is generated. This is reflected by the Rough, Model Based or Valid estimates. The decision events which have a valid estimate (based on information from existing events or from trail runs of the product design where the information is of the required level and quality) are known as the risk events. The rough and model based estimate is done when there is uncertain information (Type 2 Lu Uncertainty) to estimate the probability of occurrence of a potential reliability problem. The model based estimate refers to estimates using information from early robust design analysis, computer simulations or even practical tests on tolerances and interactions. These are still classified as uncertain information if it does not meet the required information level and quality. These events are then known as uncertain events.

These risk and uncertainty events that have been identified will need to be managed in the project. How this is done will be covered next.

### 2.3.3. Risk and Uncertainty Management

Once the project starts, risk and uncertainty management is an on-going process. There are many approaches available in Project Management Handbooks and literature on Quality & Reliability management, especially for risk management but to a much lesser extent for uncertainty management. [Lu, 2002] has developed the RQM process for risk and uncertainty management, which has been described above. A review of other commonly used approaches for uncertainty management in the consumer electronics industry by [den Ouden, 2006] has shown that only three are able to handle uncertainties. They are

- Project management – yes, but not in combination with fast time-to-market
- Learning in and across projects – partly, through cross-functional risk evaluations
- Evaluation and Testing with customers –partly, when using flexible technologies

However, even the project management approach which is the only one that can fully handle uncertainties is not suitable for uncertainty management in projects under TTM pressure. There is also a Risk Diagnosis & Management (RDM) method by [Halman and Keizer, 1994], that partly requires the detection of gaps between available and required information. This is not suitable for this research as its key focus is to diagnose and manage risks in innovative projects. So in this research, the focus will be on RQM as the process for uncertainty management.

Though the rest of the approaches that she has reviewed such as Quality Function Deployment (QFD), Failure Mode Effect Analysis (FMEA) and Design for Six Sigma (DFSS) cannot handle uncertainties, they are still necessary for risk management. In order to understand how these various risk and uncertainty approaches affect the product reliability, the four step process proposed by [Priest and Sanchez, 2001] for generic reliability management is used and adapted to the context in this research.

1. Systematically identify areas of potential technical risk
2. Determine the level of risk for each area
3. Identify and incorporate solutions that eliminate or reduce the risk
4. Continue to monitor and measure progress on minimizing risk

In step 1, the risk and uncertainty analysis is carried out to determine what are all the system parameters or failure mechanisms for the product to be developed. If there is information that can be used to model the probability and severity of the failure mechanisms, uncertainty assessment is carried out first. If the risk assessment is done first using information that is uncertain, that is there are gaps in the information, one cannot make any valid statement of the risk probability or severity. This is explained further using the model [Lu, 2002] shown below.

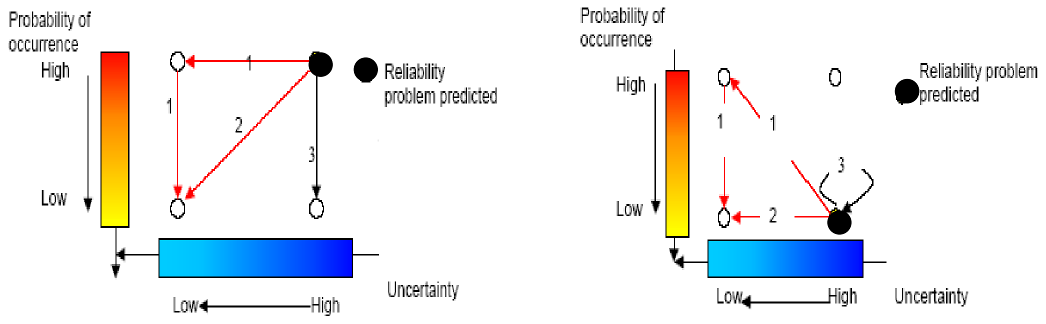

*Figure 2.3: Uncertainty Reduction is Prioritised Over Risk Reduction*

The left figure shows an event or failure mechanism depicted (by the opaque circle) with high risk probability of occurrence and high uncertainty (no information on the probability of occurrence, just a rough estimate). In the right figure, the event depicted (by the opaque circle) with low risk probability of occurrence and high uncertainty (just a rough estimate). The lines 1 and 2 (in red colour) show the desired approach where uncertainty reduction in terms of reducing the gap in information required precedes (line 1) or occurs simultaneously with risk reduction (line 2) in terms of the probability of occurrence and severity. The line 3 ( the black lines) show the incorrect approach where a focus on probability-of-occurrence reduction is applied and uncertainty is overlooked, that is no attempt made to identify any gaps in the information. In the latter approach one perceives the probability-of-occurrence as low, but while the uncertainty indication has been missing, one actually does not know what to expect. As a result unexpected problems can occur [Lu, 2002]. In other words, the uncertainty related to an event (failure mechanism) will characterize to great extent the risk of the event.

To reduce these uncertain events, three approaches are mentioned by [McDermott and O'Connor, 2002], that is to leverage on known capabilities (or subject matter experts), outsource to external consultants or choose not to resolve all the uncertainty events concurrently. Once the uncertainty is reduced through the first two approaches, the risk assessment can be carried out. During the risk and uncertainty analysis stage, if it has been determined that the failure mechanism is not new and required information is available, then risk assessment can be done immediately.

Next the applicable risk and uncertainty management approaches need to be applied to manage, monitor and measure the risk and uncertainty identified. The figure below shows a mapping of these risk and uncertainty approaches into the overall product reliability management process.

A few other tools that are used for very specific applications in the industry, such as ALT, DDM, Load-strength, Taguchi are also added in the mapping. A more detailed description of these approaches is given in the appendix.

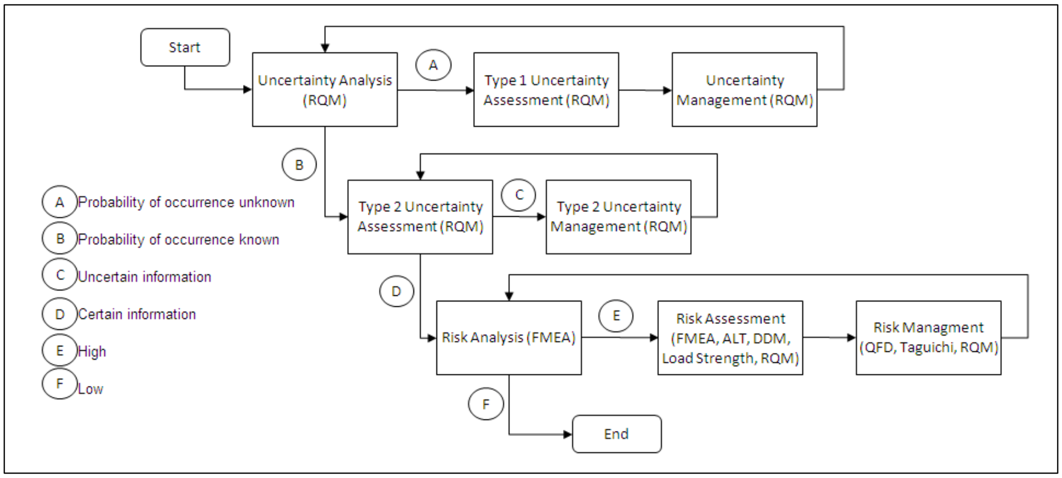

*Figure 2.4: Mapping of the risk and uncertainty management approaches to the reliability management process*

Though the adapted reliability management process is generic, not all the approaches mentioned can be applied for all types of innovations. RQM was developed for incremental type of innovations that are developed in a Concurrent Fast Product Development Process (CFPDP). Next different types of product innovations will be examined followed by a review of the different product development processes to develop these innovations.

## 2.4. Types of Product Innovations

Innovation is the use of new knowledge to offer a new product or service that customers want. According to [Porter, 1998] it is a “new way of doing things (termed as invention by some authors) that is commercialized”. A technical innovation is about improved products, services or processes, which contrasts with administrative innovation that pertains to organizational structure and administrative processes. As this research is concerned with technical innovation that improves a product, any reference hereafter to innovation will be referring to a technical product innovation.

In the research by [Lu, 2002], she developed the Reliability and Quality Matrix (RQM) to aid in identifying and reducing the uncertain reliability information involved in the fast development of derivative products. Products that are developed based on existing products with small increments. Lu had also applied the RQM method on radical product innovations, where the degree of unknown technology to the firm is very high compared with the derivative products. However it was found that the RQM method could not be used for radical innovations (in its original form) because there was no clear information on the potential reliability problems due to the high degree of unknown technology. Before we address the issue of adjustments to the RQM method, it will be necessary to find out if there are other types of innovations where the RQM method can be applied.

[Henderson and Clark, 1990] have introduced a framework for defining innovation based on the knowledge of the components and the knowledge of the linkages between them, which they call architectural knowledge.

- Incremental Innovation – enhances both component and architectural knowledge
- Radical Innovation – destroys both component and architectural knowledge
- Architectural Innovation – architectural knowledge is destroyed and component knowledge is enhanced
- Modular Innovation – architectural knowledge is enhanced and component knowledge is destroyed

The above definition is only one out of numerous (at least 15 constructs and at least 51 distinct scale items) definitions available in literature that model product innovativeness [Garcia and Calantone, 2001]. Based on a critical review of these various definitions, [Garcia and Calantone, 2001] have developed and evaluated a classification scheme based on two levels, macro versus micro and marketing versus technology perspectives. This provides the following innovation types

- Incremental Innovation – innovations occur only at the micro level and cause either a marketing or technological discontinuity but not both
- Radical Innovation – innovations that cause marketing and technological discontinuities on both a macro and micro level
- Really New Innovation – innovations that cover the combinations in between the extremes of incremental and radical innovation

Really New innovation (RNI) can evolve into new product lines (eg. Sony Walkman), product line extensions with new technology (eg. Canon Laserjet) or new markets with existing technology (eg early fax machines). It has been suggested that only 10% of all new innovations fall into the category of radical innovations [Wind and Mahajan, 1988; Rothwell and Gardiner, 1988; Griffin, 1997]. As such the bulk of innovations are of the RNI type and the incremental innovation type. The latter is similar to the derivative products mentioned by [Lu, 2002]. Though the RQM method, which was developed for incremental innovations, cannot be used ‘as it is’ for radical innovations, it may still be applicable for RNI. Furthermore, in the research by [den Ouden, 2006], she has found that incremental products have low field returns while RNI are contributing to the rise in the field returns. Hence, the focus of this research will be the applicability of the RQM method on RNI.

It is important to note that the above typology for technological innovations is relative, relative to the firm. What one firm identifies as a RNI, can be labelled as an incremental innovation by another firm. This difference is due to the differing innovation development procedures that exist in the respective firms even though they are developing the same innovation [Garcia and Calantone, 2001]. The end results for the firms will be the same though the process of reaching this result will differ significantly. The different types of product development process are covered in the next section.

## 2.5. Types of Product Development Process

There are several definitions of a product development process (PDP) in literature. According to the definitions by [PDMA, 2001] and [Clausing, 1994], the PDP in the context of this thesis is described as a process that systematically transform product ideas into new products that could be used by customers and consists of the following three basic phases.

- 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 recourse 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.

Two major types of PDP based on the degree of technical changes in products as well as their applications [Andreasen and Hein, 1987; Wheelwright and Clark, 1992] are described below.

- Radical PDPs: These PDPs develop new products (radical innovations), which generally contain new technologies and significantly change behaviours and consumption patterns in the marketplace. The first MP3 player in the market is an example of a product developed in a typical radical PDP.
- Derivative PDPs: These PDPs use proven technologies to create derivative products (incremental innovations) 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 its Pentium II processors in a typical derivative PDP.

Radical PDPs have the potential to capture a larger market share from competing products but are highly risky as they may take too long to complete the development and miss the market introduction window (eg. Apple's LISA-Macintosh in early 80s). The incremental approach of derivative PDP helps to reduce TTM as the amount of effort and learning required is less per product [Simth and Reinertsen, 1991;Wheelright and Clark, 1992]. Other advantages are the extensive reuse and leverage of past knowledge and investments as they develop successive products in the generation. Another strategy employed by the firms to reduce TTM is to reduce the product technology complexity [Smith and Reinertsen, 1991; Wheelwright and Clark, 1992; Murmann, 1994].

In situations under strong time pressure, where the early feedback from the market is used for mid course corrections of the product design, the derivative PDP is then termed as Fast PDPs bu [Lu, 2002]. The above discussion on the PDPs has focused mainly on the benefits and advantages related to TTM reduction but not on improving the product reliability. Now a review on how reliability is managed in PDPs [Brombacher et al., 2001] is discussed.

**Reactive reliability management**

- This type of reliability management is often performed in functional PDPs. This PDP is primarily function orientated [Brombacher et al., 2001] and is based on the production philosophy introduced by Frederick W. Taylor. The job is segmented into specific work tasks and focus is on increasing efficiency in these sub tasks. Reliability is then the responsibility of inspectors and is inspected at the end of the process. Product reliability problems are present but removed by inspection.

**Interactive reliability management**

- This type of reliability management is often seen in sequential PDPs. This PDP follows the principle of sequential engineering and is also known as "phased product planning" [Brown and Karagozoglu, 1993], "traditional stage gate process" [Wind and Mahajan, 1998], "phase gate model" [Meyer, 1997], etc. Essentially, the processes are performed in a linear fashion, by passing a concept or design from one functional department to another until completion. Reliability is not only inspected at each phase but there is focus on identifying root causes of reliability problems and taking corrective action to eliminate these problems.

**Proactive reliability management**

- This type of reliability management is often coupled with concurrent PDPs. This PDP follows the principle of concurrent engineering, which 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 the decision-making phase and its implementation phase are separated. Potential reliability problems are proactively predicted in the PDP and necessary (corrective) actions are implemented. Thus all required information has to be available before the PDP starts [Brooks and Schofield, 1995].

**Iterative reliability management**

- This type of reliability management is often seen in a dynamic/iterative PDP [Yazdani and Holmes, 1999]. In this PDP, interactions with customers occur right from the beginning through product prototypes 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 the context of the dynamic consumer electronics industry which is under TTM pressures, the functional and sequential PDPs are not preferred. In [Lu, 2002] research, the focus is on proactive reliability management seen in concurrent PDP because the type of innovation in the research is derivative products where all the required information is available before the PDP starts. This process where the derivative product innovation and reliability optimisation is done in increments and concurrently is termed as Concurrent Fast PDP (CFPDP) by [Lu, 2002]. In RNI where there is discontinuity in either a marketing or technological macro basis in combination with a micro level discontinuity [Garcia and Calantone, 2001], it implies that not all the required information may be available at the start due to the “newness” of the product to the market or to the firm. The lack of information (certain and unambiguous) is not limited to the product but may apply to the other factors such as market, technology, processes and organisation matters. Frequent interactions with customers must occur in order to better understand customer needs and to gather the required information.

These information exchanges must occur right from the start in the early phase of the PDP, the concept development phase. This is required because much of the product reliability is determined by the decisions made in the early phases of PDPs [Mortimer and Hartley, 1990; Musselwhite, 1990]. Some of the ways this can be done are through probe and learn techniques [Lynn, et al., 1996], working with co-opted customers or with development partners [O'Conner, 1998] as well as disciplined trial and error approaches through the concept of 'failing forward' by [Leonard-Barton, 1995].

Furthermore, the change flexibility is highest and design costs are lowest, both monetarily and time-wise in the early phases. The monetary aspect is illustrated in figure 2.5. The same reasoning can be applied on increases in development time per design change. This implies the need for proactive (iterative activity in the early phase) instead of a reactive reliability approach that replaces the costly and time-consuming philosophy of 're-do until right' by 'right first time' [Syan and Menon, 1994].

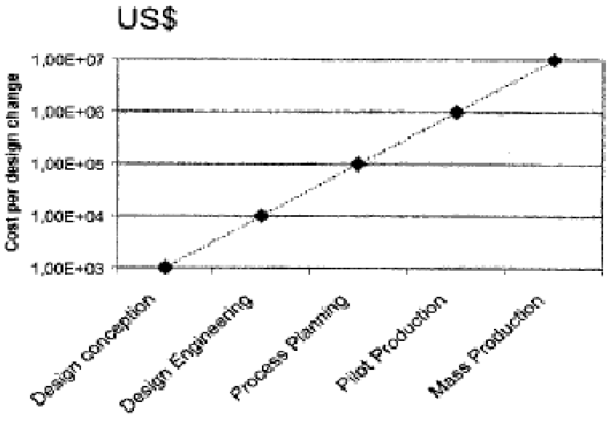

*Figure 2.5: The Cost per Change for Each Development Stage [Business Week, 1990]*

This research will thus focus on iterative reliability management of RNI developed in an Iterative PDP (IPDP), where uncertainty must be managed in addition to risk management.

## 2.6. Conclusions

The literature review above shows that current reliability management is faced with four conflicting characteristics. There is a need to develop more technologically complex products that can fulfil higher customer needs within the TTM window and in a business environment with more players. In addition, businesses are faced with increasing numbers of customer complaints on new product innovations.

These complaints are related to failures that occur in the early phases of the product life cycle and research shows that the product reliability is affected by a wider range of causes besides component reliability. Despite the improved detection and management of these reliability failures, problems may still be reported by customers due to fuzziness that exists in the reliability information.

This situation where it is not possible to determine exactly the probability of occurrence and severity of the event because there is no information or there is a gap between the required information and the available information is termed as an uncertainty. If the underlying probability of occurrence and severity can be determined, then it is termed as a risk.

There are many methods, processes and tools for risk management but the list is much shorter for uncertainty identification and management. The RQM process, which was developed to identify and manage risk and uncertainty information related to the reliability of derivative products developed in CFPDP, appears to be the most suitable process for uncertainty management in projects under TTM pressure.

In the context of this research, where we are dealing with Really New Innovations (RNI) that are developed in an iterative product development process (IPDP), not all the information that is required is available. This leads to the research proposition:

*Research Proposition: Since RQM can be used to manage the uncertainty aspect of reliability information flows in CFPDP, it can similarly be used for RNI in IPDP .*

The next chapter will focus on investigating the applicability of RQM to RNI in IPDP for reliability management, which includes the aspects of uncertainty.

# CHAPTER 3 ANALYSIS OF RQM IN THE FIELD

In this chapter a case study approach is used to carry out an analytical generalisation, instead of a statistical generalisation, to validate the research proposition and thereby answer research question 1. This is due to the nature of the subject matter under research, where each case may range from a few months to a few years and the limited accessibility to confidential information relating to the innovation. Hence, the aim of using a few samples is not to prove statistically that the proposition holds all the time but to demonstrate that the proposition may not hold sometimes.

The chapter starts with some background information on RQM, the RQM process, and how it was implemented in the industrial case studies in section 3.1. Section 3.2 defines the evaluation approach for the case studies that focuses on the uncertainty aspect, followed by an overview of the industrial cases in section 3.3. The industrial case results are analysed in section 3.4 to answer the research proposition. In section 3.5, the causal factors for the industrial case results are identified and research question 1 is answered. Conclusions are drawn in section 3.6.

## 3.1. RQM in the Field

[Lu, 2002] analysed the use of QFD and FMEA in derivative PDPs under TTM pressure. As these products employ proven technologies to quickly integrate mature building blocks from existing products it should be theoretically possible to fully predict and prevent reliability problems [Lu, 2002]. Actual field information showed otherwise (many unexpected reliability problems were observed) due to the presence of uncertainty in the PDP, which was not managed by the use FMEA or other quality tools that required certain information for risk predictions. In order to manage uncertainty and risk in derivative PDPs under TTM pressure, RQM was developed. More detailed information on RQM is given in appendix A.

### 3.1.1. The RQM Process

The analysis of RQM in the industry was done in the company mentioned in section 3.3. In that company, the RQM was part of the mandatory set of tools and methods that were required to be used during each and every project and was incorporated into the standard product innovation procedures. The detailed manual on the process or guidelines are found in the Design Quality Assurance (DQA) department and has been translated to a step-by-step process into a computerised RQM spreadsheet tool. Besides providing the guiding framework for the RQM process, it also serves as the reference for archiving all the risk and uncertainty related issues related to the project as well as the checklist to ensure all the critical steps are carried out.

The RQM process is started from the early phases of concept development right up to the production phase, where the close loop feedback is used for learning purposes for the next projects. At each of the eight mandatory milestones in the New Product Introduction (NPI) process of the company (figure 3.5), the progress and status of the RQM process must be reported to the management team so that there is visibility on product reliability.

The RQM application is conducted with the help of a trained RQM facilitator who is from the DQA department and is attached full time to the project team for the duration of the project but is accountable primarily to the DQA Manager, who has a direct link the General Manager and the Management Team. Hence the facilitator has relative independence and freedom from bias, yet is fully involved in the project team. To be qualified as a RQM facilitator, one must be competent in reliability knowledge and tools, undergo formal training by the DQA manager or external consultant familiar in RQM and have facilitated the RQM application in a minimum of two projects under the supervision of the DQA Manager (or external consultant familiar with RQM if the DQA Manager is not a qualified RQM facilitator). In the company under research, there were a total of five qualified RQM facilitators, including the DQA Manager.

### 3.1.2. The Initial Meetings

At the initial risk briefing to the project team, the facilitator along with the DQA Manager conducts a briefing and training on the RQM and its application to the entire project team, which includes the extended team members from Product Management, Program Management, Pilot Production, Supplier Based Management and Costing. The topics will cover the objective of RQM, the process steps (Table 2.1), expected input, level of involvement, amount of time required and assurance that issues raised are for the purpose of risk management (and not to be used negatively in performance appraisal). The output of the session is an awareness of the entire process and agreement on the number of sessions that are required for the RQM application as well as their willingness to cooperate.

The subsequent RQM sessions are then planned by the project manager in consultation with the RQM facilitator, as this will ensure that the ownership and responsibility for the product quality and reliability remains with the project manager and his team. This will also reduce the impact of framing effects [Tversky and Kahneman, 1982] as the respective functional expert and project manager is responsible for their respective areas that impact the product reliability. Depending on the complexity or the type of product innovation, the project manager may schedule one or more sessions to complete steps 1 & 2 (listed in table 2.1) between the marketing representative, key customer account team, the various functional architects, supplier based management and the RQM facilitator in order to draft out the customer requirements.

### 3.1.3. The Risk and Uncertainty Management

The next series of meetings that the project manager will schedule is done among the core project team members consisting of the various functional architects (electrical, mechanical, dynamics, optics, drive system), engineering process, equipment, pilot production, factory quality, supplier based management and the RQM facilitator. The risk and uncertainty analysis (steps 3 & 4 of table 2.1) is carried out and where there is sufficient information available, risk assessments (step 5 of table 2.1) are done and the probability of occurrence for each event is recorded into the RQM spreadsheet tool. If there is a gap between the required information and the available information, then the team will make a rough estimate for the uncertainty assessment relating to the probability of occurrence of the event. The core team members can then leverage on known capabilities (or subject matter experts), outsource to external consultants or choose not to resolve all the uncertainty events concurrently [McDermott and O'Connor, 2002]. Other approaches for uncertainty assessment include early robust design analysis, computer simulations or even practical tests on tolerances and interactions.

All of the risk and uncertainty assessments are verified by the RQM facilitator before the input is accepted and updated into the RQM tool. In situations where there are differences of opinions, then a third developer or another DQA representative is consulted and acts as a referee to determine the final estimates for the event. Observations and feedback from the meetings are compared with other meeting findings from other projects through the discussions with other design quality staff in the DQA Review Meetings and with development specialists in the Technical Review Meetings, both of which are held prior to early milestone meetings. In this way an aggregation of opinions is achieved.

The above discussion covers the aspect of managing the probability of occurrence of risk and uncertainty related to product reliability. The severity aspect or the impact of the risk is also tracked and managed in step 5 of table 2.1 by assigning a “High” or “Low” impact to the event. Each product reliability related risk or uncertainty that is posted in the RQM is accompanied by action plans with details, e.g. who, when, how and what are documented and presented to the management for decision at milestone meetings. The RQM facilitator or the DQA representative will ensure that the project team are tracking and resolving all of the agreed events or issues. If the need arises to highlight or escalate a particular event due to an unsatisfactory resolution, he can do so via the DQA manager either at the DQA review meeting, Technical review meeting or at the milestone meeting itself.

The above description explains how the RQM process is applied in the company where the case studies are carried out. However, it was observed that the company applied the RQM process to all the products it was developing regardless of whether the product is an incremental, really new or radical innovation though the RQM was developed for incremental products as there was no other alternative method that was known to the company for uncertainty management. The typical changes, among other things, which the company carried out when developing the different types of innovation is adaptations to the NPI process from a concurrent approach to an iterative approach. Hence there is a need to determine the effectiveness of RQM to be used to help manage the uncertainty aspect of reliability information flows for really new innovations developed in an IPDP so that the research proposition can be validated.

*Research Proposition: Since RQM can be used to manage the uncertainty aspect of reliability information flows in CFPDP, it can similarly be used for RNI in IPDP.*

Though the company uses the customer feedback in its iterative PDP during the early phases, the information is used for the product development and not to check the effectiveness of the RQM. For the RQM effectiveness, it depends on the feedback from the field (consumer) or customer, which is useful as input for the next generation of products as the design for the current product would be frozen and any design changes would be costly (figure 2.1). Hence an approach which uses the available information in the early phases of the PDP as feedback information to evaluate the effectiveness of the RQM for RNI developed in an IPDP is described in the next section.

## 3.2. Analysis method

In chapter 2, it was discussed that in order to manage the risk and uncertainty aspects of reliability information flows in RNI developed in IPDP, a capable method needs to meet the following criteria:

- Proactive management
- Effective uncertainty management
- Effective risk management

This section discusses an analysis method that can be used to evaluate RQM using the above criteria.

### 3.2.1. Proactive management

Proactiveness is judged on whether the risk and uncertainty estimates were done early enough in the PDP. [Lu, 2002] has stated that RQM is to be applied at different moments in the PDPs in order to identify and monitor uncertainties and risks. In the early phases of the PDP, when the flexibility is highest [Syan and Menon, 1994] and cost of changes is low [Business week, 1990], RQM should be applied to identify and predict potential product reliability problems, including the aspects of uncertainty. In this approach, the uncertainties can be managed and reduced as shown by line B in figure 3.1 [Lu, 2002].

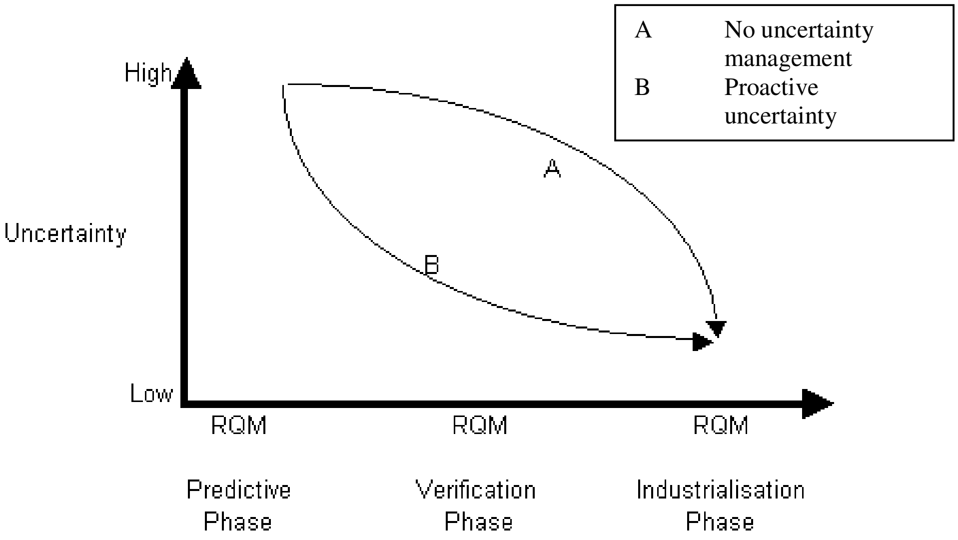

*Figure 3-1: Managing Uncertainty in PDP*

Therefore, to be proactive the method has to be used in the predictive phase. In order to measure proactiveness, a “+” and “-” are used to indicate whether RQM has been or has not been used during the predictive phase respectively.

**Criterion 1: Proactiveness in the predictive phase**
\+ used during the predictive phase of the PDP
-- not used during the predictive phase of the PDP

### 3.2.2. Effective risk management

RQM is a predictive method used to identify product reliability uncertainties and risk. If this method works as expected, limited product reliability problems will be observed at the latter part of the verification phase of the PDP, when the product is ready for shipment to the customer. This can only be done when the risk predictions on the probability of occurrence of an event have good quality and create an adequate focus on the relevant potential product reliability problems. However, risk predictions made on uncertain information results in poor predictions [Lu, 2002] in early PDP.

Uncertainty prediction therefore needs to be measured first as an effective risk management depends on an effective uncertainty management.

### 3.2.3. Effective uncertainty management

In section 2.3, it has been shown that there are two types of uncertainty. Logically both need to be managed effectively. [Lu, 2002] shows that minimal amount of uncertainty due to a lack of information (Analysis uncertainty) is present in derivative PDP. She shows that RQM then is capable of managing the remaining uncertainty due to ‘available but not usable’ information (Lu uncertainty), effectively for derivatives.

However, RNI contain a high degree of innovativeness. A considerable amount of Analysis uncertainty is present in those PDP, which needs to be managed proactively. In this thesis, effective uncertainty (both analysis and Lu) management in IPDP in terms of the probability of occurrence of an event is thus split into effective type 1 and type 2 uncertainty management which are defined below.

**Effective type 1 uncertainty management**

Effective type 1 uncertainty management means that no unexpected failure mechanisms are identified after the design has been frozen. The correct list of relevant failure mechanisms has to be known before design freeze in order to prevent reliability problems resulting from type 1 uncertainty. In other words, most type 1 uncertainty has to be removed, by the last RQM session of the predictive phase.

Then comparing the list of confirmed failure mechanisms at the verification phase with the list of failure mechanisms at the last milestone in the predictive phase before the design is frozen would reveal if type 1 uncertainty has been managed effectively.

The symbols used in the analysis are:

| | |
|---|---|
| $\hat{x}_{a_i}$ | The predicted percentage of product failures due to the predicted failure mechanism $a_i$ just before the design is frozen (last prediction in the predictive phase) |
| $x_{a_i}$ | The predicted percentage of product failures due to the predicted failure mechanism $a_i$ when there is no uncertainty. |
| D | The difference between the $\hat{x}_{a_i}$ and the $x_{a_i}$ caused by uncertainty in the $\hat{x}_{a_i}$ |
| $y_{b_j}$ | The verified percentage of product failures due to verified failure mechanism $b_j$ at the verification phase. |
| A = | The predicted list of relevant failure mechanisms just before the design is frozen (last prediction in the predictive phase) |
| B = | The verified list of relevant failure mechanisms at the verification phase. |
| A = | $\{a_1, a_2, \ldots.., a_n\}$ |
| B = | $\{b_1, b_2, \ldots.., b_m\}$ |

Type 1 uncertainty has not been managed effectively for a failure mechanism E if $E \notin A$ , $E \in B$ . This can be due to Lu or Analysis uncertainty as illustrated in figure 3.2.

The total amount of risk not predicted due to ineffectively managed type 1 uncertainty then is the failure probability sum of all failure mechanisms E which are element of data set B but not A: $\sum_{E \notin A, E \in B} y_E$

A numerical example is given below in figure 3.2 to explain the uncertainty evaluation approach.

*Example 3.2: Assume there are four failure mechanisms Y3, Y4, Y5 and Y6 which were not identified in the predictive phase due to an ineffectively managed type 1 uncertainty. The total amount of risk not predicted due to ineffective type 1 uncertainty management = Y3 + Y4 + Y5 + Y6 = 4%+12%+2%+5% = 23%. Among these 23% amount of rejects, 4% is due to Lu uncertainty and 19% is due to Analysis uncertainty.*

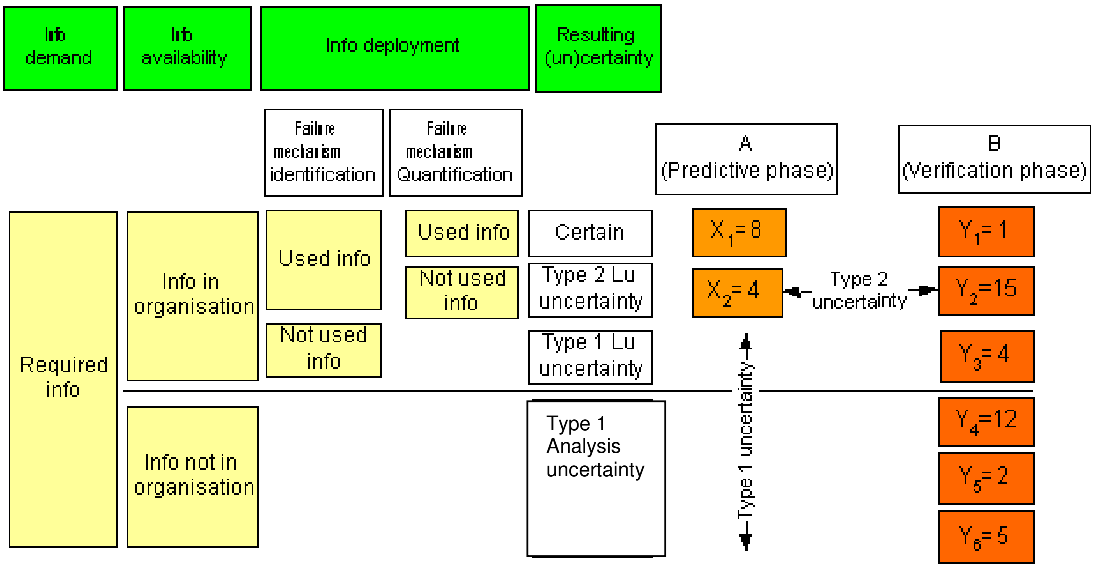

*Figure 3-2: Identifying ineffective type 1 and 2 uncertainty management.*

## Effective type 2 uncertainty management

Effective type 2 uncertainty management is only possible for failure mechanisms that have no type 1 uncertainty. For these known failure mechanisms, risks have to be quantified. When type 2 uncertainty has been managed effectively, the quantifications are executed correctly and therefore risks can be reduced effectively. Thus for a predicted known failure mechanism E, type 2 uncertainty has been managed effectively if no additional risk is identified after product design has been frozen. This means no risk increases should be observed.

However, if the type 2 uncertainty has been managed ineffectively there still is uncertainty present in the last risk estimation just before the design is frozen [$\hat{x}_E$]. Both the type 2 uncertainty present in this estimation and eventual risk reduction measures have to be considered to explain the difference between the actual (verified) failure probability [$y_E$] and the last estimation [$\hat{x}_E$]. This is visualised in figure 3.3 below.

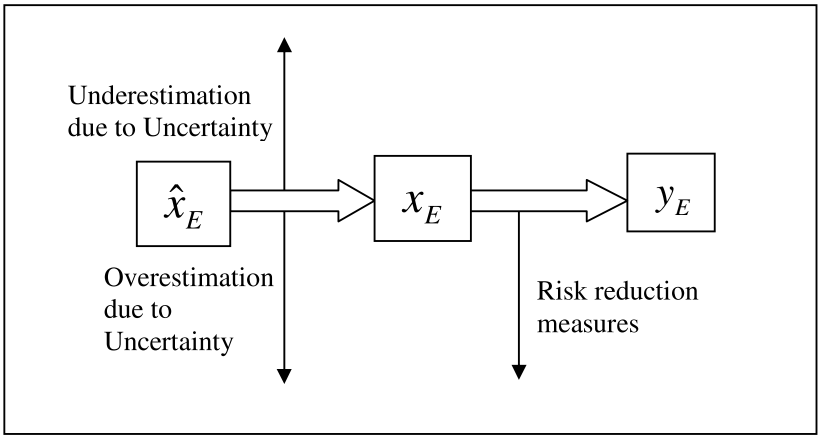

*Figure 3-3: Forces that Explain the Difference between the Last Risk Prediction and the Verified Risk when Type 2 Uncertainty is Present in the* $\hat{x}_E$

As there is only one arrow pointing upwards, a risk increase [$y_E > \hat{x}_E$] can only be caused by the uncertainty present in the last risk estimation. A risk increase thus indicates an ineffectively managed type 2 uncertainty (failure mechanism 2 in figure 3.2). However, care has to be taken with conclusions regarding risk decreases. These are not necessarily an indication of effective type 2 uncertainty management as risk reduction measures can ‘pollute the image’. This is explained in appendix F. Thus for a single known failure mechanism E ($E \in A$ , $E \in B$)

| | |
|---|---|
| [$y_E > \hat{x}_E$] | RQM ineffectively manages type 2 uncertainties |
| [$y_E \leq \hat{x}_E$] | This is the desired situation. However, it is not possible to draw exact conclusions on the effectiveness of type 2 uncertainty management. In appendix F it is explained that ineffectiveness only occurs in very limited times in this situation and if ineffectiveness is present it is less severe than that when $y_E > \hat{x}_E$. Therefore this analysis will focus on |

identifying the ineffectiveness when $y_E > \hat{x}_E$.

The amount of risk not predicted due to ineffectively managed type 2 uncertainty then is the increased failure probability sum of all failure mechanisms E which are the element of both data sets A and B and that satisfy $y_E > \hat{x}_E$ : $\sum_{E \in A \cap B \cap \{E | y_E > \hat{x}_E |\}} (y_E - \hat{x}_E)$

Referring back to the example 3.2 shown in figure 3.2, the type 2 uncertainty has been managed ineffectively for failure mechanism 2. This failure mechanism was incorrectly estimated at 4% instead of 15% due to ignored type 2 Lu uncertainty. The total amount of risk not predicted due to ineffective type 2 uncertainty management is y2 – $\hat{x}_2$ = 15% – 4% = 11%

**Measuring RQM's uncertainty management ineffectiveness**

Ineffective type 1 or 2 uncertainty management results in incorrect or inaccurate risk estimates in the predictive phase of the PDP. This inaccurateness can then be expressed by the ratio of the unidentified risk due to ineffective uncertainty management and the total risk that should have been predicted. The total risk that should have been predicted represents the risk that would have been predicted if limited uncertainty due to effective uncertainty management of RQM in the predictive phase.

This risk is equal to: $\sum_{E \notin A, E \in B} y_E + \sum_{E \in A \cap B \cap \{E | y_E > \hat{x}_E |\}} (y_E - \hat{x}_E) + \sum_{E \in A, E \notin B} \hat{x}_E$

The first and second term represent the risk not predicted (due to respectively ineffective type 1 and 2 uncertainty management) while the third term represents the predicted risk.

RQM manages type 1 uncertainty effectively if no new failure mechanisms are identified after design has been frozen. This means that the risk in the last milestone of the predictive phase has been predicted accurately. The higher the percentage of unpredicted risk in the predictive phase, the more ineffective RQM is in managing type 1 uncertainties and the more inaccurate the risk prediction. This will be measured with the type 1 inaccuracy ratio.

Type1 inaccuracy ratio (T1)= $$\frac{\sum_{E\notin A,E\in B} y_E}{\sum_{E\notin A,E\in B} y_E + \sum_{E\in A\cap B\cap\{E|\,y_E>\hat{x}_E|\}} (y_E-\hat{x}_E) + \sum_{E\in A,E\notin B} \hat{x}_E}\times 100\%$$

The same reasoning applies to the percentage of unanticipated risk in the predictive phase due to type 2 uncertainty. The type 2 inaccuracy ratio is defined as:

Type 2 inaccuracy ratio (T2)= $$\frac{\sum_{E\in A\cap B\cap\{E|\,y_E>\hat{x}_E\}} (y_E-\hat{x}_E)}{\sum_{E\notin A,E\in B} y_E + \sum_{E\in A\cap B\cap\{E|\,y_E>\hat{x}_E|\}} (y_E-\hat{x}_E) + \sum_{E\in A,B} \hat{x}_E}\times 100\%$$

A “+” and “-“ are used to indicate effective and ineffective uncertainty management respectively and they are defined as follows:

**Criterion 2: Type 1 Inaccuracy (The percentage of risk in the last milestone of the predicted phase that has not been identified due to unknown failure mechanisms)**

+ Type 1 inaccuracy ratio = 0
- Type 1 inaccuracy ratio > 0

**Criterion 3: Type 2 Inaccuracy (The percentage of the risk in the last milestone of the predicted phase that has not been identified due to uncertainty in the risk quantification)**

+ Type 2 inaccuracy ratio = 0
- Type 2 inaccuracy ratio > 0

Referring to the example 3.2 in figure 3.2 again, the total risk that would have been identified in the predictive phase if uncertainty would have been low or negligible = (4%+12%+2%+5%) + (11%) + (8%+4%) = 46%.

*RQM's type 1 inaccuracy ratio = (4%+12%+2%+5%)/46% = 50%*

*RQM's type 2 inaccuracy ratio = 11%/46% = 24%*

Due to very ineffective type 1 and 2 uncertainty management by RQM respectively 50% and 24% of the risks were not predicted.

The next section presents the industrial case studies where the RQM method is applied and evaluations carried out on the data collected.

## 3.3. Industrial Case Study

Case studies are a powerful tool for gathering information and understanding the real conditions that are occurring in organisations [McCutcheon and Meredith, 1993]. This approach is used to validate the research proposition defined in Chapter 1. Cases are selected based on the type of innovation (RNI), type of PDP (Iterative), RQM application (yes) and type of development environment (consumer electronics product development under TTM pressure). Next an overview of the company and the product development process it practices is described.

### 3.3.1. Optical Company

Optical Company (OC)[2] develops and manufactures innovative products for optical storage applications. It delivers its state-of-the-art products to Original Equipment Manufacturers (OEMs) worldwide. In a market that is characterized by ongoing innovation OC is one of the dominating players.

The product portfolio of OC comprises drives, subassemblies and components related to audio, video, data and gaming playback and rewritable products in CD and DVD technologies for the consumer recording, gaming, automotive infotainment and PC storage markets. OC supplies its customers with products varying from subassembly components (optical pickup units) to mechanisms/loaders, to modules/engines including electronics and software, to complete finished products like CD-RW drives. It conducts extensive product development activities in the Europe and Asia. Optical Company also operates manufacturing facilities in China, Malaysia and Hungary.

OC is operating in the innovative market of consumer electronics, that is the audio-video and computer market. This market is turbulent because there is a very high rate of new product introductions that include derivative (incremental innovations), really new innovations (RNI) and radical products. The product under research in this case study is the optical pickup units (OPUs). The Singapore office undertakes research and development activities in components, sub-assemblies and complete optical drives. It is also responsible for the entire product development process, from feasibility study to manufacturing and marketing.

### *3.3.2.* Product Development Process in OC

In OC the product development process is called New Product Introduction (NPI) process which is derived from the well documented description of the SPEED Product

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[2] Names for the company and the various projects in the case studies have been intentionally changed for confidentiality reasons

Creation Process [Philips, 1994]. The stepwise approach in SPEED is adapted so that development activities of the various functions can run in parallel similar to concurrent PDPs and consists of eight mandatory milestones (depicted in figure 3.4). The NPI process allows for customers to be engaged in the predictive phase so that the customer requirements can be better understood through intensive information exchanges, especially if the product being developed is a radical or really new innovation. Hence the NPI process can be characterised as either a concurrent or iterative PDP depending on the type of innovation being carried out by the particular project. Each milestone involves a review of the status of the PDP compared to its original targets. A go/no-go decision is made by the management that results in the project being allowed to progress or be stopped. The eight milestones are grouped into the predictive phase (Concept Start, Product Start, Specification Release and Release for Engineering Samples), verification phase (Release for Qualification Samples and Industrial Release) and industrialisation phase (Production Release and Mass Production Release). These three phases as defined in the guidelines from OC (figure 3.5) are similar to the above three phases as identified from literature.

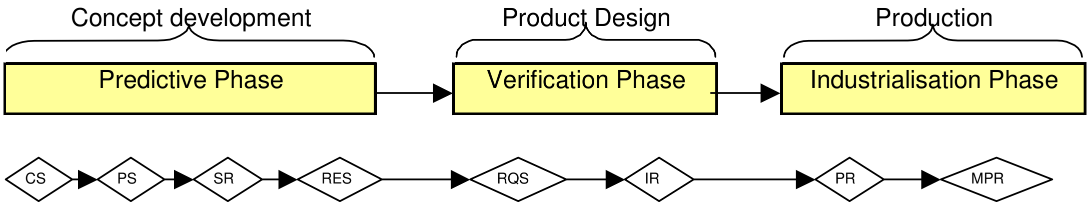
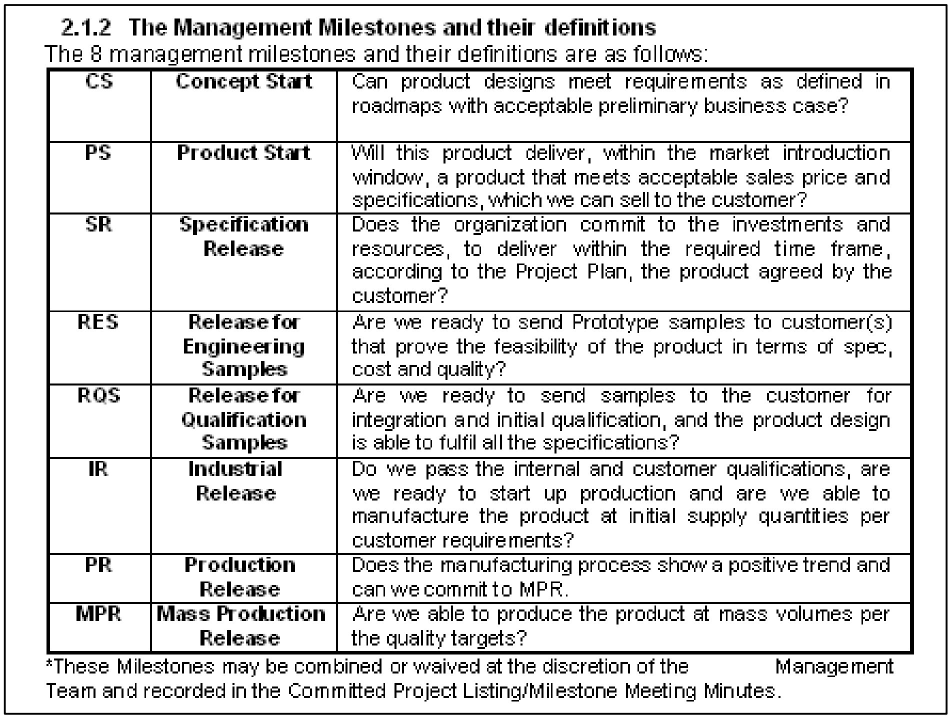


*Figure 3.4: OC Milestones within the PDP Phases*

This enables the findings from the case study to be generalized and be externally valid to PDP in the consumer electronics industry as the intent and aim of each phase is similar. What differs is the terminology used.



**2.1.2 The Management Milestones and their definitions**

The 8 management milestones and their definitions are as follows:

| | | |
|---|---|---|
| **CS** | **Concept Start** | Can product designs meet requirements as defined in roadmaps with acceptable preliminary business case? |
| **PS** | **Product Start** | Will this product deliver, within the market introduction window, a product that meets acceptable sales price and specifications, which we can sell to the customer? |
| **SR** | **Specification Release** | Does the organization commit to the investments and resources, to deliver within the required time frame, according to the Project Plan, the product agreed by the customer? |
| **RES** | **Release for Engineering Samples** | Are we ready to send Prototype samples to customer(s) that prove the feasibility of the product in terms of spec, cost and quality? |
| **RQS** | **Release for Qualification Samples** | Are we ready to send samples to the customer for integration and initial qualification, and the product design is able to fulfil all the specifications? |
| **IR** | **Industrial Release** | Do we pass the internal and customer qualifications, are we ready to start up production and are we able to manufacture the product at initial supply quantities per customer requirements? |
| **PR** | **Production Release** | Does the manufacturing process show a positive trend and can we commit to MPR. |
| **MPR** | **Mass Production Release** | Are we able to produce the product at mass volumes per the quality targets? |

*These Milestones may be combined or waived at the discretion of the Management Team and recorded in the Committed Project Listing/Milestone Meeting Minutes.

*Figure 3.5: Extract from OC Project Guideline*

## 3.3.3. Case Selection

Two Really New OPU development projects conducted in an IPDP approach that were on-going at the time of the research were selected as the cases to test the research proposition. It was decided to collect data in real time rather than retrospectively to control for history effects that so often weaken case study research. The data collection was gathered at multiple times within each of the case study to effectively track both the progress and learning that occurred. The information gathered during the various meetings which involved senior management, functional managers, product architects, developers (electronics, mechanical, optical, dynamics, equipment, drive system) supporting functions (Costing, Supplier based management), marketing, customer representatives, engineering process, factory quality and production was documented in the RQM spreadsheet tool. In cases where there was ambiguity, the DQA representative would have a one-to-one meeting with the respective developers to clarify doubts. Overall, more than 40 different people were involved in both the case studies.

The facilitator that was assigned to both the case studies was the same qualified facilitator who had completed more than 6 RQM applications in various other projects. This would ensure that the RQM was applied in a similar manner in both the case studies. Furthermore the DQA manager himself closely supervised the case study to ensure that the RQM was applied as per the RQM guidelines (manual). A brief description of each case is presented next, while the details are in the appendix C.

### 3.3.4. Case Description

The OPU16[3] development project is an Optical Pick-up Unit. It is the key component of the CD module that houses the laser. OPU16 is part of the full height OPU generation and is considered as a micro level marketing discontinuity as it was meant to target a new market for the company. The deliverable for this project was a significant reduction in Bill of Material (BOM) costs together with a significantly simplified manufacturing process and assembly equipment that required a macro level technological discontinuity to the project team. Its predecessor is the OPU24. It was developed in Belgium unlike the OPU16, which is the first OPU that is developed by OC at its new location in Singapore by a new development team. As per the classification scheme by [Garcia and Calantone, 2001], this product would be classified as a RNI.

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[3] The project codes in this thesis refer to internal company information which is confidential, but the author had full access and has received full permission to use in the context of this thesis

The second case is OPU46. It was the first product of a new generation of half-height OPUs and is considered as a micro level marketing discontinuity as it would create a new market segment of slimmer end products. It qualified as a RNI project as it required a new form factor, product architecture, change of components and also changes in the production process which constitute a macro level technological discontinuity.

Figure3.6 shows the classification scheme proposed by [Garcia and Calantone, 2001]. The above two OPU case study is indicated by the (++) based on the information derived from the project assignments.

| | Radical | Really New | Really New | Really New | Really New | Incre mental | Incre mental | Incre mental |
|---|---|---|---|---|---|---|---|---|
| Macro | | | | | | | | |
| Marketing discontinuity | x | | x | | x | | | |
| Technology discontinuity | x | x | | x | | | | |
| Micro | | | | | | | | |
| Marketing discontinuity | x | x | x | x | | x | | x |
| Technology discontinuity | x | x | x | | x | x | x | |
| OPU16 | | | | ++ | | | | |
| OPU46 | | | | ++ | | | | |

*Figure 3-6: Classification Scheme by [Garcia and Calantone, 2001].*

### 3.3.5. Case Data Collection

OC uses three main product reliability performance measurements in RQM for each of the milestones. These measurements, measured in percentages, give an indication of the product quality at the end of their own production process, at their customer's production process and at the consumer in the field.

*FOR (Fall-Off Rate), which refers to the rejects in the production line within the OC manufacturing process. Initial FOR is obtained during the verification phase.*

*CBR (Customer Belt Reject), which refers to the rejects in the production line of the customers with relation to OPUs from OC.*

*FCR (Field Call Rate), which refers to the rejects from the field (after being sold to the consumers) due to failures of OPUs from OC.*

These are all predicted risk quantifications. Ideally one wants to compare the predicted FOR, CBR and FCR with the validated values of these figures from respective production end-of-line-tests, customer inspections and field feedback. However, the FCR information from the field has a strong focus on logistics [Petkova, et al., 2000] and the process used to collect the information from the consumers is often driven by availability, cost and time [Molenaar, et al., 2002] and not on product reliability. As such, the nature of product reliability information from the field is very different from the product reliability information that is being researched in this project. Similarly, the information from the customer is also very much influenced by the logistics arrangement and quality agreement between the customer and the producer. This results in variation in the product reliability information obtained from the customer [Philips internal data] for the same product that is shipped to them. Therefore it was decided to focus on the FOR measurements. For a producer shipping to an OEM customer (business-to-business) situation, consumer-related reliability problems are less eminent anyway, as the customer requirements determine to a large extent how customers use the product [Lu, 2002].

The actual FOR becomes available in the verification phase (RQS and IR milestones) where production trial runs are executed. The sample size built and tested during for the RQS and IR milestones are about 480 and 1000 products respectively. The test results provide a good statistical approximation of the production FOR. Since the products are being produced and shipped to customers, the RQS and IR risks represent actual risk and thus uncertainty is assumed to be negligible.

The information obtained for review and analysis is gathered from multiple sources of evidence within the project team's archival data and documented information in the organisation. This information were then cross checked through informal interviews with the management, project team and subject content experts within the organisation as mentioned in the earlier part of this chapter.

### 3.3.6. Case Analysis Method

In this section, the detailed case analysis method is discussed based on the general method discussed in section 3.2

**Proactive management**

The proactiveness is judged by reviewing the dates that the risk and uncertainty predictions were made and documented by the project team. These are cross checked with the planned project milestones to identify in which phase of the PDP the uncertainty predictions were made and whether it is during the predictive phase of the project.

**Effective type 1 uncertainty management in OC**

Effective type 1 uncertainty management means that the uncertainty is gradually identified in the subsequent CS, PS, SR and RES milestone of the predictive phase as more information is obtained. When managed effectively uncertainty should be low in the last committed milestone of the predictive phase, as this is the last milestone before the design is frozen [Lu, 2002]. The list of failure mechanisms in the last committed milestone of the predictive phase then has to be compared with the list of failure mechanisms at the RQS milestone (in verification phase) to calculate the Type 1 inaccuracy ratio.

**Effective type 2 uncertainty management in OC**

The approach is similar to the analysis of type 1 uncertainty management effectiveness except that for type 2 uncertainty management effectiveness the list of known failure mechanisms is needed, that is the failure mechanisms E that are part of the last committed milestone of the predictive phase and RQS milestone in the verification phase. A comparison is made between the risk estimates due to the failure mechanisms E at the respective milestones to calculate the Type 2 inaccuracy ratio.

## 3.4. Case Analysis Results

### Proactive management

As can be seen from table 3.1 the development team used RQM thrice in the OPU16 project, once during each phase of the PDP process. The OPU46 project team used it more times during the predictive phase and verification phase as the user-interface of the supporting RQM spreadsheet tool was made much easier for data entry. As RQM was used in the predictive phase for both the projects, it shows that RQM was used proactively.

| | OPU16 | OPU46 |
|---|---|---|
| Number of times RQM was used | | |
| Predictive phase (PS – RES) | 1 | 3 |
| Verification phase (RQS – IR) | 1 | 2 |
| Industrialisation phase (PR – MPR) | 1 | 1 |

*Table 3-1: RQM applications during each PDP phase*

### Effective type 1 uncertainty management

The list of failure mechanisms in the verification phase (RQS milestone) had been formulated based on the failure mechanism analysis done in this phase by the engineers. The list contained 17 new failure mechanisms compared to the predictive phase (PS milestone) adding a total risk $\sum_{E \notin A, E \in B} y_E$ of 6.8% to the project (appendix). This resulted in a Type 1 inaccuracy ratio of 35% for the predictive phase as can be seen in figure 3.4.

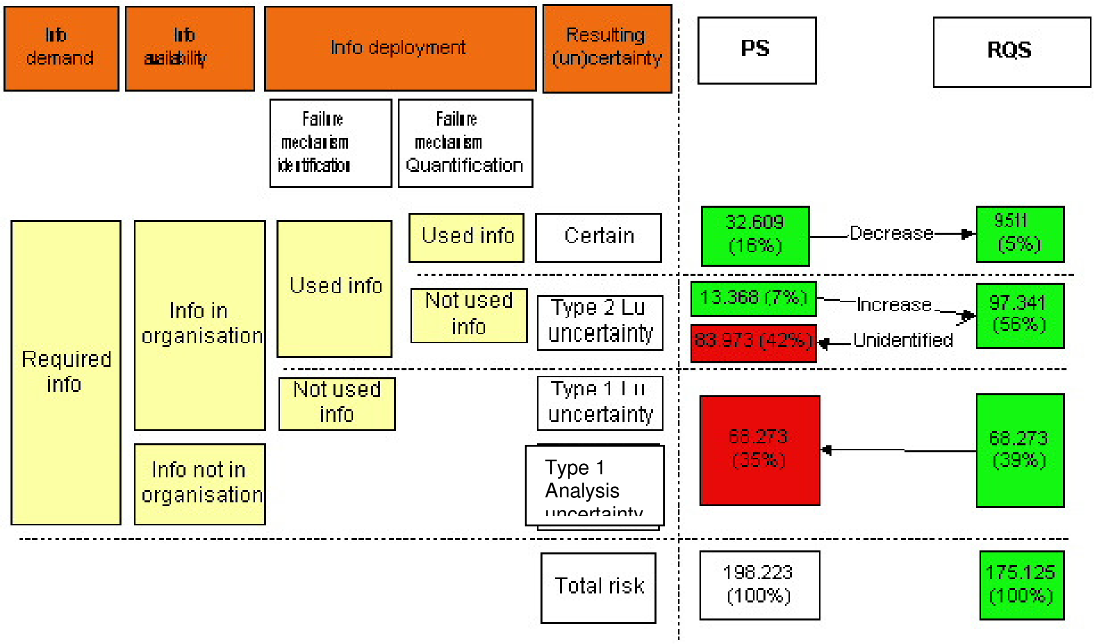


*Figure 3-4: The Amount of Identified (green) and Unidentified Risk (red) with RQM in the OPU16 Case Study*

In OPU46, the failure mechanisms identified in the predictive phase were similar. However, in the verification phase (RQS Milestone) 11 new failure mechanisms were identified. These 11 failure mechanisms added 67.5% additional risk to the risk ( $\sum_{E\notin A,E\in B} y_E$ ) at the verification phase (RQS milestone). This resulted in a type 1 inaccuracy ratio of 86% indicating a very ineffectively managed type 1 uncertainty, i.e. 86% of the risk had not been predicted in the predictive phase due to ineffective type 1 uncertainty management.

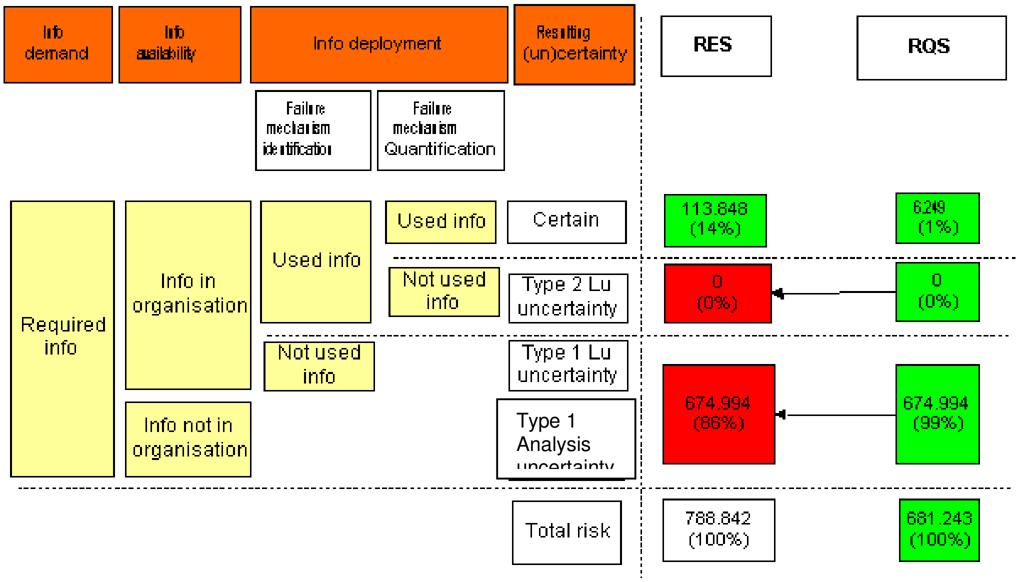


*Figure 3-5: The Amount of Identified (green) and Unidentified (red) Risks with RQM in the OPU46 Case Study*

### Effective type 2 Uncertainty management

For OPU16 project, 12 of the failure mechanisms known in the predictive phase showed a risk increase in the verification phase (appendix C). They showed a total percentage increase [ $\sum_{E\in A\cap B\cap\{E|y_E>\hat{x}_E|\}}(y_E-\hat{x}_E)$ ] of 8.4%. The calculated type 2 inaccuracy ratio is 42%.

In OPU46 project, none of the identified failure mechanisms showed an increase in the percentage value (appendix and figure 3.5), thereby resulting in a type 2 inaccuracy ratio of zero. The findings were further analysed and the informal interviews conducted revealed that the developers in the project team took a more cautious approach to estimating uncertainties. The uncertainties that were identified were assigned risk estimates only if they were confident of the risk quantification. If they could not make accurate risk estimates, the developers chose not to make any estimates. Hence these would end up as type 1 uncertainty. Though RQM effectively managed type 2 uncertainties in the radical OPU46, the type 1 uncertainties were even less effectively managed. The above findings are summarised in the table below.

| | OPU16 | OPU46 |
|---|---|---|
| Uncertainty Effectiveness | | |
| Type 1 inaccuracy ratio | 35% | 86% |
| Type 2 inaccuracy ratio | 42% | 0% |
| Total uncertainty inaccuracy ratio | 77% | 86% |

*Table 3-2: Summary of uncertainty inaccuracy ratios*

At this juncture it is necessary to highlight the message from the above figures for Type 1 and 2 inaccuracy ratio in table 3-2, which show an enormous dispersion. The interviews conducted with the developers in OPU46 shows that they chose not to make estimates, even rough estimates, unless they were very certain. Hence the 86% of type 1 inaccuracy ratio could have included type 2 inaccuracy ratio as well and as such it is more meaningful to compare the total uncertainty inaccuracy ratio, which is 77% for OPU16 and 86% for OPU46.

Furthermore the formulas that have been proposed in section 3.2 have reduced the uncertainty and risk to single figures. However the values should not be taken as absolute, which shall be discussed later. On the contrary, it should be viewed more as a high level indicator of the probability of occurrence in the context of the trend for each identified failure mechanisms or events. That is whether the identified failure mechanism or event showed an increasing trend or not. If there was an increase (as in the failure mechanism 1, 2 and 3 in table 3-3), it would mean an ineffective management while a level or reduced trend (as in failure mechanism 4) would mean an effective management. More details of each and every failure mechanism and trend are available in appendix.

| No | Case Study | Failure Mechanism | PS (ppm) | RQS (ppm) | Uncertainty Type | Trend |
|---|---|---|---|---|---|---|
| 1 | OPU16 | Beam Measurement | | 3514 | Type 1 | Negative |
| 2 | OPU16 | CD Adjustment | 4096 | 14606 | Type 2 | Negative |
| 3 | OPU16 | OPU Housing | 1 | 29427 | Type 2 | Negative |
| 4 | OPU46 | OPU Housing | 11771 | 2083 | Type 2 | Positive |

*Table 3-3: Extract of Failure Mechanism Trends*

The figures in Table 3-2 should not be taken as absolute figures due to the following reasons. Firstly, the developers who were involved have feedback that risk and uncertainty quantification is not an easy task especially when there are gaps in the information. Furthermore, it is not always possible to reduce the various aspects of risk as mentioned in chapter 2 into single number. This is similar to the finding from [Shapira, 1994] that transformation of a multidimensional phenomenon to one number might not be adequate or helpful, though the participants in the study indicated the need for such a number. This way of thinking runs counter to statistical analysis, where the more likely outcomes get more attention. It is possible that the decision makers' thinking about risk may be affected more by what they perceive to be the most representative piece of information. [Taversky and Khaneman, 1974] showed, the use of heuristics such as representativeness may not relate in a simple way to summary statistics.

Secondly, due to the dynamic nature of RNI being developed in an IPDP, it has been observed that the project teams work hard to reduce uncertainty on some dimensions so that they can work on other aspects of the project, that is they temporarily suspend work on some uncertainties. While this may appear as an incorrect behaviour, actively managing so much uncertainty simultaneously is no practical. Whether it is appropriate or what are the decision criteria for the 'stopping' strategy for learning are clearly issues for further research.

Therefore, in view that the RQM was applied correctly by a qualified facilitator and yet there are failure mechanisms or events that have been identified which were not managed effectively in both the case studies, it could be concluded that RQM is not effective to manage uncertainty in RNI developed in IPDP in both of the case studies, thereby answering research question 1. This indicates that the research proposition may not hold all the time in the company.

*Research Proposition: Since RQM can be used to manage the uncertainty aspect of reliability information flows in CFPDP, it can similarly be used for RNI in IPDP .*

*Research question 1: How effectively can risk and uncertainty aspects of reliability be managed for RNI developed in IPDP using the RQM method?*

Since it is concluded that RQM could not simply be used in IPDP to effectively manage uncertainties, the next logical step is to identify the associated causal factors.

## 3.5. Causal Factors Identification

To identify causal factors for the ineffectiveness of RQM in managing type 1 and 2 uncertainties, multiple sources of data were analysed. Analysis was done on the documented project archival data such as customer specification requirement, commercial specification, technical specification, production report, customer report, problem analysis report, corrective action report, milestone meeting minutes, results of FMEA, RQM data and reliability tests reports. This was cross checked through informal interviews conducted with the management, project manager and various project team members.

A total of 40 failure mechanisms from various failure causes were identified in the two RNI of OPU16 and OPU46. These failure causes are shown in table 3.4 will be discussed in the next sections.

### 3.5.1. Causes for Failures due to Type 1 Uncertainty

Type 1 uncertainty can be caused by lack of information within the organisation (Analysis uncertainty). It can also arise from a situation when information is available in the organisation but it is not used by the organisation (Lu uncertainty). The full analysis of the failures is listed in appendix C. Examples of representative failures from the two case studies due to type 1 uncertainties is discussed in depth.

**Uncertainties due to Equipment Gage**

Equipment gage refers to the repeatability and reproducibility of the equipment [Montgomery and Runger, 1994]. RQM only focuses on sources of uncertainty related to the product parts and process; it does not cover the gage capability of the equipment used to assemble the parts. The "Alpha-beta and Gluing" in OPU16 process was not identified as a major uncertainty during the predictive phase but there was 3% of unexpected rejects during the verification phase. This was due to the poor gage capability of the glue dispensing equipment that resulted in an inconsistent quantity of glue dosage for each OPU. The same failure cause was also noticed in the OPU46 process where there was 8% rejects at the verification phase which were not identified.

**Uncertainties due to operator assembly skills**

The "Cut laser leads & insert into housing" process resulted in 0.6% of rejects in the OPU16 project. The operators at that station were required to pull down fully on the press-in jig arm. Failure to do so would result in incomplete insertions of the laser into the laser holder thereby resulting in deviated optical paths, which is not acceptable. During the training of the operators, there was insufficient emphasis on the need to pull down the press-in jig arm fully. As such, when the production speeded up to meet the production output targets, the operators at the station did a partial pull down of the press-in jig arm in order to reduce the cycle time at their station. Similarly, in the OPU46 project, the mounting of the BSP was not identified as a potential uncertainty that will be influenced by the operators' assembly skills. This led to 1.3% of unexpected rejects in the verification phase. This element of operator assembly skills is beyond the scope of RQM and hence it was not identified as an uncertainty in the predictive phase for both the projects.

**Uncertainties arising from process design**

The HOE assembly and adjustment process is process where an optical part called HOE is assembled into the OPU and adjusted until the required optical performance is obtained. In the OPU16 project, HOE spring was not identified as a potential risk in the early risk prediction activities of the project but later on resulted in 2282ppm of rejects (appendix C). Based on the reject analysis, the project team identified that the main causes of the rejects were due to process design issues as follows:

- Improper sitting of the adjustment tool on to the HOE before adjustment can take place such that gives a false adjustment reading is obtained
- Over-adjustment that leads to an unstable fit of the HOE spring. This results in the spring being dislodged at some later period and the HOE adjustment being affected.
- Poor gluing of the HOE spring due to operator skill

This aspect of process design which requires multi-disciplinary knowledge of the various elements that interact and affect the product design such as adjustment equipment limitations, process assembly constraints and adhesives application issues are beyond the scope of RQM, which focuses on the process steps and parts involved.

Each of these failure causes resulting from ineffective uncertainty identification during the predictive phase becomes risks during the verification phase of the project. There were a total of 28 failure mechanisms arising from the 7 failure causes which were not related to uncertainties in product parts or processes or at another deeper level within the scope. Though the RQM does not prevent the inclusion of the above areas outside the main scope, it is left to the discretion of the developers. It was observed that the developers did the minimum that was mandatory for the RQM method due to the time and resource constraints. These instances and failures causes which were not identified are summarised in table 3.4 below.

### 3.5.2. Causes for Failures due to Type 2 Uncertainty

Analyses of the Type 2 uncertainty showed that the project team was unable to accurately estimate the risk prediction even though they had identified the failure mechanisms. In other words, they were able to reduce the uncertainty in identifying the Type 1 uncertainty for the 12 failure mechanisms identified in OPU16 project thereby converting it into risks. However, due to insufficient information, they were not able to quantify these uncertainties correctly in order to reduce the Type 2 uncertainties into quantifiable risks.

An example of this is the “DVD adjustment” station, which was identified as potential risk area that may result in OPU rejects. However as the project team was new to the equipment and had no previous information on the risks, they could not accurately quantify the risk at the predictive phase. Since a rough estimate was made that the potential risk was 0.09%, they did not place priority on the risk reduction. The actual rejects during the verification phase was found to be 3.1%, which was much more than the risk estimation in predictive phase. The similar cause is applicable to each of the 12 cases shown in table 3.4 below.

The analysis of the OPU46 project revealed that the project team did identify uncertainties but did not make an estimate of the risk prediction unless they were very confident of the prediction. In these situations, they did not indicate the identification of the uncertainty through risk predictions, which led to the risks surfacing later as type 1 uncertainties.

| Uncertainty | Failure Cause | OPU16 | OPU46 |
|---|---|---|---|
| Type 1 | Efficiency of technical support staff | 2 | 1 |
| | Equipment design | 1 | 1 |
| | Gage for equipment | 1 | 3 |
| | Operator assembly skills | 2 | 2 |
| | Part design | 5 | 1 |
| | Training not effective | 3 | 1 |
| | Process design | 3 | 2 |
| Type 2 | Quantification of risk | 12 | 0 |

*Table 3-4: Overview of Failures Causes and Occurrences in the Verification Phase due to Type 1 & 2 uncertainties*

Regardless of whether the project team made risk predictions on the identified uncertainties, the risks due to either type 1 or 2 uncertainties still occurred at the verification phase as shown in table 3.2. To summarise, RQM is unable to manage the uncertainties in OPU16 and OPU46 because it explicitly covers product parts and production processes but not other areas (that are left to the discretion of the developers) that can give rise to type 1 uncertainty. Secondly, there is a lack of information with the project team to quantify the identified risks, resulting in type 2 uncertainty.

## 3.6. Conclusions

Based on the industrial case study results related to root cause analysis, it can be concluded that RQM is unable to proactively manage the uncertainties in RNI developed in IPDP. This is due to two main causes.

RQM does not cover all elements of RNI as it only focuses on product parts and process and there is lack of appropriate information generated by the RQM method to enable quantification of the identified risks.

As such, there is a need to identify the design criteria for a suitable method to manage all risk and uncertainties in RNI. Besides being proactive, the method needs to have more coverage than RQM and enable the quantification of uncertainties. The next chapters will derive the design requirements based on the identified criteria so that a suitable prototype design can be developed to proactively manage risk and uncertainty in RNI. This will lead to answers to research question 2 and the research objective can be addressed.

# CHAPTER 4 REQUIREMENTS AND CONCEPTS FOR UNCERTAINTY MANAGEMENT

It has been discussed in Chapter 2 that uncertainty as well as risk needs to be managed for RNI from the early phases in IPDP; uncertainty must first be identified and reduced before risk reduction. In this chapter, the design requirements for effective uncertainty management of RNI in IPDP are first identified in section 4.1 and explained in section 4.2. These requirements are then translated into design criteria in section 4.3 followed by the conclusion in section 4.4.

## 4.1. Design Requirements

The analysis of the industrial case studies in chapter 3 revealed that RQM does not cover a wide scope of uncertainties for RNI in IPDP. This results in Type 1 uncertainties outside the scope of product parts and production processes not being identified by RQM. Even if Type 1 uncertainties had been identified, the further quantification of it also results in Type 2 uncertainties. Therefore a new method which covers a wider scope of Type 1 uncertainty and reduces Type 2 uncertainty related to risk quantification needs to be developed. This method should meet the following four design requirements and the related design criteria.

**Design requirement 1: Proactive uncertainty management.**

As shown in chapter 2, under strong TTM pressure, it is necessary to identify potential uncertainties and risks for RNI early in the PDP where there is more flexibility in making the design choices that can positively influence the product reliability. As such the new tool must enable the proactive reliability management.

### Design requirement 2: Able to identify a wider scope of uncertainty

In the previous chapter, the causes of unmanaged Type 1 uncertainties in the industrial case studies were identified. The case results showed that RQM (as applied based on guidelines) focused only on Type 1 uncertainty related to product parts and process and not other areas that are left to the developers' discretion. As a result, the Type 1 uncertainties that are not associated with product parts and processes were not identified. In order to detect the Type 1 uncertainties outside the scope of product parts and process for RNI in IPDP, the scope of the new method must be enlarged.

### Design requirement 3: Uncertainty identification method must be flexible enough to select macro elements and decompose these into micro elements

The very nature of RNIs that involves innovative technologies and processes implies that "one size cannot fit all". In the industrial case studies in chapter 3, it was identified that Type 1 uncertainties not only result from elements inside and outside the scope of the product parts and processes, but also from micro-elements under these elements. To elaborate, an identified Type 1 uncertainty in the macro element of product part resulting from the choice of a new material for that part may need to be sub-divided into micro-elements. This new material coming from a new supplier may have uncertainties in the micro-elements of supplier capability, supply chain issues, material property. The micro-elements of supply chain may have uncertainty in the material availability and lead times for the delivery, while the micro-element of material property may have uncertainty in the material's thermal stability and design stability under different stress and strain conditions. This decomposition of the macro-element into micro-elements is shown in the figure below.

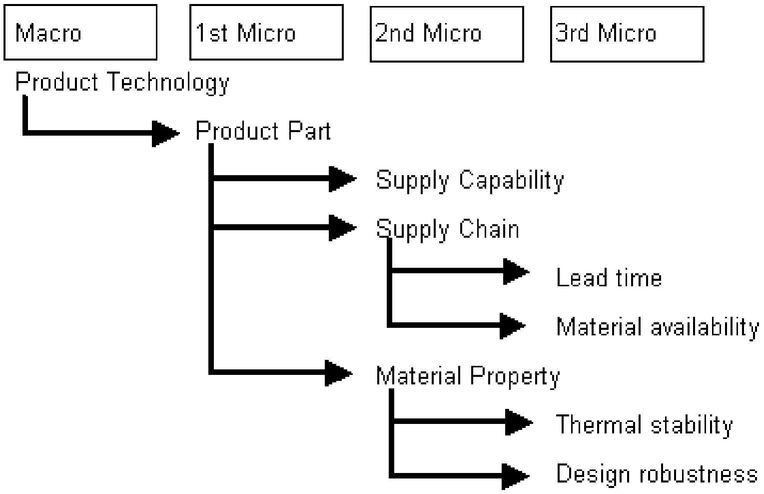
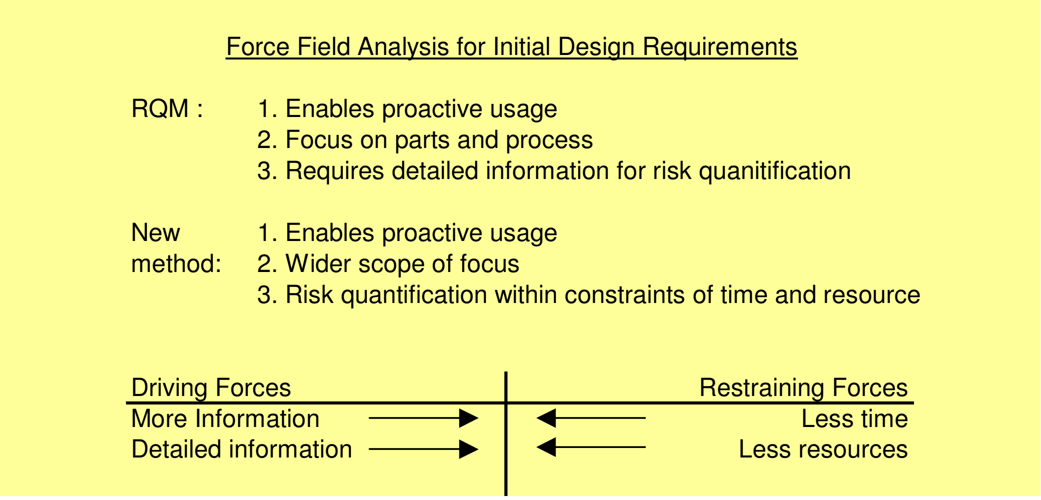


*Figure 4-1: Decomposition of Macro-element into Micro-elements*

**Design requirement 4: Enabling uncertainty estimation within constraints of limited time and resources.**

Design requirement 2 requires a wider scope of uncertainty identification while design requirement 3 requires in-depth uncertainty identification. Once all these uncertainties are identified, they can be reduced by identifying the required information to make an uncertainty assessment and then a risk assessment once all the information becomes certain. The risk assessment to quantify the risk can be done using the existing quality methods mentioned in figure 2.4. However, all the risk analysis and identification mentioned require very detailed and specific information. Hence the project team needs to allocate resources and time, which is often unavailable in radical PDPs [Minderhoud and Fraser, 2005], and likewise in IPDP which also operate under the same TTM pressure.

To analyse this paradoxical situation where on one hand there is a push to get more detailed data and on the other hand there is a constraint of time and resources, a force field analysis is carried out [Lewin, 1951]. The current state is the RQM, while the desired state is the new method. The driving and restraining forces for the move from the current state to desired state is listed down as shown in figure 4.2.



Force Field Analysis for Initial Design Requirements

RQM :
1. Enables proactive usage
2. Focus on parts and process
3. Requires detailed information for risk quanitification

New method:
1. Enables proactive usage
2. Wider scope of focus
3. Risk quantification within constraints of time and resource

*Figure 4-2: Force Field Analysis of the Opposing Requirements*

The new method must enable uncertainty analysis and assessment by reducing the effects of the restraining forces or increasing the effects of the driving forces. Increasing the driving forces of getting more information and information that is detailed, is done in CFPDP  by re-using validated or proven building blocks in the design or by starting concurrent engineering activities in parallel [Lu, 2002].

Using proven building blocks is practical in incremental innovations developed in CFPDP but not for RNI developed in IPDP. For RNI developed in an IPDP implies that more resources are required or more time if the resources are fixed, but this is a major restraining force for IPDP. To resolve this, the new method must enable uncertainty estimation within the constraints identified.

Before proceeding to develop the design criteria based on the above requirements, it is necessary to carry out literature review to substantiate the 4th design requirement.

## 4.2. Information Resolution

The preceding section has shown that in order to effectively reduce uncertainty it is necessary to cover uncertainty in elements beyond product parts and process as well as micro-elements under each element. To do an uncertainty assessment, more information which is detailed and specific is also required. However, the above requirements need to be met within the constraints of time and resource. Literature review below shows that this situation is not unique.

### 4.2.1. Counter Intuitive Design Concept: *Less-is-More*

In a radical PDP (or an IPDP) under time pressure, it is not possible to wait until all detailed information is available [Brombacher, 2000]. Yet an organisation has to make a decision of whether to proceed with the project based on whatever information it has at that time. Choices have to be made within these constraints. [Breiman et al., 1993] provides a simplified yet more accurate way of classifying heart attack patients who are rushed into hospital emergency rooms according to risk status rather than complex statistical classification methods. It omits the majority of possible measured predictors and quantitative information by using only yes/no answers to a 3 step process for heart attack patient classification.

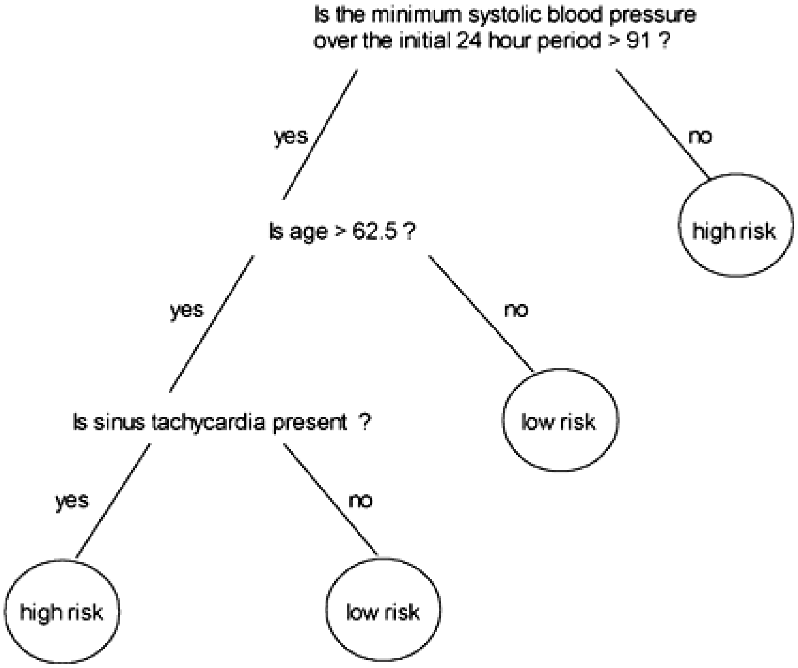


*Figure 4-3: Decision Tree for Classifying Incoming Heart Attack Patients into High Risk and Low Risk Patients, adapted from [Breiman et al., 1993].*

This counter intuitive finding that fast and frugal decision making can be as accurate as strategies that use all available information and expensive computation [Gigerenzer et al., 1999] will be adapted and used in the next section to develop some ideas on how to apply the above counter intuitive design concept to managing uncertain information in RNI within the constraints of IPDP.

The effectiveness of using heuristic (simple cue) decision making is also proven in the domain of reducing avalanche accidents which is highly uncertain. [McCammon and Hageli, 2004] have found that applying a checklist of seven simple cues to potential avalanche slopes represent the most effective decision strategy for avalanche terrain, based on accident data from the US. Similarly, the mandatory use in Switzerland of the 3x3 method developed by Werner Munter (researcher with the Swiss Federal Institute for Snow & Avalanche Research in Davos and mountain guide, published a book in German called 3x3 Lawinen: Risikomanagement im Wintersport. Third edition

Agentur Pohl & Schnellhammer, Garmisch Patenkirchen, Germany, 2003) for risk reduction when making terrain decisions for skiing has reduced accidents by 55%. (Though the term risk reduction is used, it is more about uncertainty reduction as there is little certain information about when the avalanche will happen prior to the occurrence)

Within the practical constraints of a "limited time" and incomplete knowledge of the snow pack, Munter came up with a new method based on Franklin Vestes rule of **Pattern Recognition** for determining avalanche potential in a given area. His method is based on the idea that there are two modes of thinking: Scientific or "left" brained; rational, conscious thought, slow, differentiating, based on scientific details and Operational or "right brained"; Quick, responsive, intuitive, gut-feeling, based on past experiences and able to recognise patterns; and the acceptance that we will need to use both modalities in our decision making processes in order to make better decisions. Shown below is the simplified reduction method.

| Criteria | Dry Snow Conditions (fresh powder) | Wet Snow Conditions (snow clumps easily) |
|---|---|---|
| Below 35deg | X | X |
| Above 40% | XX | XX |
| Outside Sector North (NE, N, NW) | X | N/A because S aspects are often more dangerous under these conditions |
| Visible Tracks (in his research Munter noted that in 60% of all accidents there were no visible **tracks** **note plural**) | X | X |
| Respect Distance (10 meters between group members) | X | X |

(Ratings: Considerable=XXX Moderate= XX Low =X)

*Table 4.1: Munter's Matrix for Decision Making*

Studies in his research have shown that in order to make better decisions, the maximum number of variables we can deal with is only 5 (optimally is 3), these variables should have no more than 5 different values (optimally is 3). More information than this quickly leads to an overload and does not increase the quality of the decision. It is better to have one basic approach, less details are better.

From an economic theory standpoint, [Simon, 1976] contends that in today's complex world individuals cannot possibly obtain or process all of the necessary information required to make fully rational decisions. Hence they try to make decisions which are good enough and that represent a reasonable or acceptable outcome. He called this less ambitious view of human decision making as "bounded rationality" and described the results it brought as "satisficing" (as a portmanteau of "satisfy" and "suffice"). In simple term, this "acceptable level of uncertainty hence risk" to make satisficing decisions can be referred by the adagium of "less-is-more".

### 4.2.2. "Less-is-More" Concept for Uncertainty Management in RNI developed in IPDP

The new method must be designed such that it can use less or minimum information to enable the correct uncertainty assessment.

Analysing the types of information available in the PDP from the project archival data from the industrial case studies in chapter 3, it is observed that there are different ways of describing any particular failure mechanism or event depending on the available information and time. To illustrate with an example, consider the lifetime of laser for an OPU. It can be described as having a lifetime of 850 power-on hours or having a lifetime between 500 hrs to 1000 hrs or having a longer lifetime compared to a previous laser model.

The definition of minimum or resolution which is relevant for this research is as follows:

- The minimum difference between two discrete values that can be distinguished by a measuring device. [MIL-STD-188].
- A measurement of the smallest detail that can be distinguished by a sensor system under specific conditions [DOD dictionary].

The above classical definition can be applied very easily if one is referring to a single attribute that is detectable by a measurement or sensor system device. In the event of a multi-attribute product, one can still apply the definition above. As a result, granularity is increased by decomposing the product down to single attributes. However, the definition above does not adequately address the different types or levels of information that are available in the PDP.

Reviewing other means of defining levels or measurements reveals that the level of measurement of an element in mathematics and statistics describes how much information the numbers associated with the element contain. The four levels of measurement identified by [Stevens, 1951] are:

1. Nominal measurement.
2. Ordinal measurement.
3. Interval measurement.
4. Ratio measurement.

Adapting both the concepts of resolution and measurement levels and applying it to information, we develop a new information dimension called information resolution. This has four resolution levels of information as follows:

**1. Nominal Information –** The information is a name or label. The only comparisons that can be made between the information values are whether they are equal or not. (e.g., *the laser can be powered on*)

**2. Ordinal Information –** The information has all the features of nominal information and also represents the rank order (1st, 2nd, 3rd etc) of the entities they describe. Comparisons of more and less can be made, in addition to equality and inequality. (*e.g., laser A has longer power on lifetime than laser B*)

**3. Interval Information –** The information values have all the features of ordinal information and also are separated by the same interval. In this case, differences between arbitrary pairs of information values can be meaningfully compared. Operations such as addition and subtraction are therefore meaningful. (*e.g., laser A has a power on lifetime between 500 hrs to 1000 hrs*)

**4. Ratio Information –** The information value has all the features of interval measurement and also has meaningful ratios between arbitrary pairs of information values. Operations such as multiplication and division are therefore meaningful. (*e.g., laser A has a power on lifetime of 850 hrs*)

Applying this definition of information resolution on the information available for RNI in IPDP, minimum information consists of nominal or ordinal information. The interval or ratio types of information are more detailed information which may exist for known elements. Based on the literature review and new information resolution concept, the 4th design requirement is redefined along the information resolution concept as follows:

**Revised design requirement 4: Enabling uncertainty estimation with minimal information.**

The next section will identify the necessary design criteria for the prototype design method to fulfil.

## 4.3. Design criteria formulation for a Different Uncertainty Management Method

It has been shown that RQM is unable to effectively manage the risk and uncertainties for RNI in IPDP. The causes identified were that RQM focused on uncertainties resulting from product parts and process. The unidentified uncertainties came from elements outside the scope of product parts and processes as well as from a lack of information for the quantification of identified risks. The measurable design criteria to fulfil the design requirements are formulated here. In the rest of this chapter, the term uncertainty shall be used to refer to both uncertainty and risk unless specifically mentioned otherwise.

The design criteria are discussed in close relation with the PDP discussed in Chapter 3. It has been discussed in section 3.2.1 that uncertainties and risks should be identified in the early phases of the PDP because it gives the highest flexibility for making design improvements [Syan and Menon, 1994] and the total cost is lower [Business week, 1990]. Hence the design criteria should indicate how early or in which phase the uncertainty and risk management is applied in the PDP.

**Design requirement 1: Proactive uncertainty management.**

**Design Criterion 1: Proactiveness in the predictive phase**

+ Used during the predictive phase
- Not used during the predictive phase

The 2nd design requirement requires the new method to cover a more complete range of uncertainties. This is unlike the incremental innovations done in a CFPDP, where many of the factors that are external to product parts and process are stable or there is information available to the project team. The method must have a process in place, which guides the project team to start from a top down business perspective of the project and enable them to cover the most comprehensive or complete scope possible. This ensures requirement 2 is met.

**Design requirement 2: Able to identify a wider scope of uncertainty**

**Design Criterion 2: Completeness**

+ Scope covers the total product development project
- Scope is limited to product parts and process development

Next it is necessary to ensure the method can be adapted or changed easily to remain relevant RNI developed in IPDP where the uncertainty can occur from a much wider scope in the project. Any changes or modifications in the method to cater for the changes should not become a major task in itself, especially when there are tremendous pressures and constraints in the product development process. It must enable the project team to decompose the uncertainties from macro-elements into micro-elements. Hence the method must have a structural design that enables this flexibility.

**Design requirement 3: Uncertainty identification method must be flexible enough to select macro elements and decompose these into micro elements**

**Design Criterion 3: Flexibility**

+ Able to select uncertainty macro-elements and decompose it to micro-elements

- Unable to select uncertainty macro-elements or decompose it to micro-elements

Once the method is designed such that it is more complete and can be adapted to match the differing uncertainties, the usage of it should be easy enough for use without the need to have vast amounts of data entry or require detailed high resolution information from complex simulations and experiments [Gigerenzer, et al., 1999]. This will ensure the method can be used by all project team members rather than a specialist or a statistician. The time taken for applying the method will be minimal so that it does not severely affect the project progress nor cause it to be dropped in priority when there is time constraint [Minderhoud and Fraser, 2005].

**Design requirement 4: Enabling uncertainty estimation with minimal information.**

**Design Criterion 4: Information Type**

+ Use low resolution information

- Use high resolution information

Any method that can be used proactively and is able to meet the criteria of completeness of the total project scope will enable uncertainties from much wider scope to be identified. Designing it such that it can be modified easily and allow for full flexibility would ensure the method remains relevant within the rapidly changing environment in IPDP. Finally, the new method must be able to use low resolution information that requires minimal time so that project team members use it and use it properly. The diagram below sums up the design criteria necessary for the new method and it shows the limitations of the currently available RQM method.

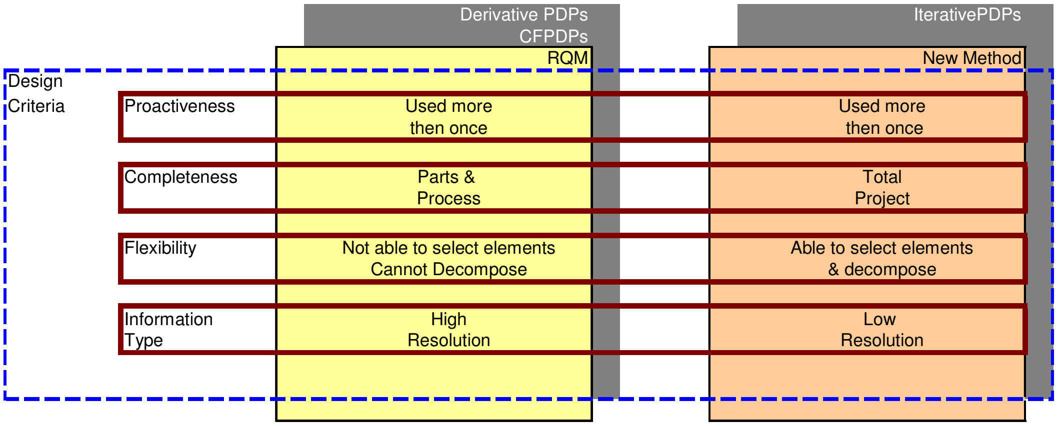


*Figure 4-4: Overview of Design Criteria*

## 4.4. Conclusion

Based on the findings in the previous chapter that RQM was unable to effectively manage uncertainties in RNI developed in IPDP, four design requirements for the new method were developed. The first three design requirements of proactiveness, more complete scope and more flexibility would lead to a situation where more detailed information is required which is not easy to obtain in IPDP which are under tremendous TTM pressure and certain information is not available due to the nature of RNI.

It has been shown above that simple heuristics perform comparably to more complex algorithms which require specific quantified information. Simplicity leads to robustness. Adapting this concept along with the concepts of resolution and measurement levels in order to apply it to ‘information’, we developed a new information dimension called information resolution.

Information resolution defines information as nominal, ordinal, interval or ratio type of information. In the context of RNI developed in IPDP, where there is little information due to the type of innovation and time pressure, minimal information that is required for uncertainty and risk estimation refers to nominal or ordinal information type. This nominal or ordinal information is also known as low-resolution information. With this, the 4th design requirement of enabling uncertainty estimation with minimal information was defined.

Based on literature review and the design requirements, research question 2 is answered.

*Research question 2: What are the design criteria that can be used to manage risk and uncertainty aspects of reliability of RNI being developed in IPDP?*

The four design criteria that have been identified (as shown in Fig 4.4) to design the new method are:

1. Proactiveness – It should be used in the predictive phase
2. Completeness – Scope which covers the total project
3. Flexibility – Able to select the macro elements and decompose them into micro-elements
4. Information type – Able to use low resolution information

In the next chapter, a prototype design for the new method is proposed. It is then applied on the industrial case studies to indicate the validity of design criteria

# CHAPTER 5 DESIGN PROPOSAL FOR RELIABILITY AND QUALITY MATRIX LITE

It has been shown in previous chapters that key focus of RQM is on uncertainties related to product parts and process. It is unable to identify and manage uncertainties of RNI developed in IPDP. The rigid process that uses quantitative and specific information requires much time and resources, which is scarce in IPDP as shown in chapter 2. In order to fulfil the research objective, the new design criteria have been developed in chapter 4. The new method must be usable in the early phases of the IPDP, have a more complete scope over the total project, should be fully flexible and able to use low resolution information.

*Research Objective: To identify the design criteria for a method that can be used to manage reliability, especially the risk and uncertainty aspects, of RNI in an IPDP.*

In section 5.1, the building blocks necessary to fulfil the design requirements and criteria for the prototype method are developed. The Reliability and Quality Matrix Lite (RQM-Lite) design method is proposed in section 5.2, which includes the process flowchart and detailed description. The relation between RQM and RQM-Lite is discussed in section 5.3 followed by the conclusion in section 5.4.

## 5.1. Building Blocks for Uncertainty Management Method

The first design requirement of proactiveness is a process related requirement whilst the requirements of completeness, flexibility and ability to use low resolution information are method related. The building blocks to fulfil the method related requirements will be developed first followed by how the proposed design should be integrated into the existing product development process.

### 5.1.1. Uncertainty Categorisation to Ensure Completeness

Uncertainty in IPDP is influenced by many factors as shown in section 3.5. Categorising uncertainty factors can be challenging, as there are so many different interpretations of the scope of the terms used and the differing categorisation may arise because researchers' from many scholastic communities may be addressing select audience. [Sanchez and Heene, 2004] describes three uncertainty elements depending on the degree of "unknown": unknown-unknown uncertainties, known-unknown uncertainties and known-known uncertainties. [van Asselt, 2000] provides another topology of uncertainties based on the variability in the project environment. [Luijten, 2003] defines three elements of uncertainty namely, market, product technology and industry uncertainty.

The top-down approach should be taken to ensure that the analysis is conducted holistically in a similar approach to the fault tree analysis pioneered by [Fussell, 1976]. Starting from the top, it will be necessary to determine what the contributing factors are at the next level that may impact the product reliability. [Keizer, et al., 2002] has made a very extensive and clear list of risks that cover a broad range of issues. The 12 categories he has mentioned (listed below) are used as the starting reference to capture a more complete scope for uncertainty and risk analysis.

1. Product Family & Brand Positioning
2. Product Technology
3. Manufacturing Technology
4. Intellectual Property
5. Supply Chain & Sourcing
6. Consumer Acceptance
7. Trade Customer
8. Competitor
9. Commercial Viability
10. Organisational & Project Management
11. Public Acceptance
12. Screening & Appraisal

In the context of RNI developed in IPDP, it is required to make satisficing decisions based on an acceptable level of uncertainty hence risk (literature review in section 4.2). It is proposed that the project team starts with the above 12 categories and narrows it down to 3 (or up to 5) categories which shall be referred to as macro-elements from now on.

The final choice of macro element category depends on which of these elements represents the significant change or innovation compared with the previous product and also ensures the maximum scope of coverage. For example, if the project team is developing a product in a Business-to-Consumer (B2C) industry, then market uncertainty is important [Moriarity and Kosnik, 1989; Halman, et al., 2001; Song and Parry, 1994]. This is different from a Business-to-Business (B2B) industry that this research is based on. In a B2B industry where the customers are fewer and there are specific key account teams that know the customer very well, the element of market uncertainty may not be one of three macro-elements.

### 5.1.2. Flexibility in Categorisation – Information Granularity

To fulfil the requirement of flexibility in categorisation, the method must provide a means and ensure that the macro-elements can be decomposed into finer information granules when required. The 12 macro-element categories from [Keizer, et al., 2002] can be split into 142 micro-elements. Not all of these micro-elements may be equally significant for all projects. This implies that the macro element and 1st level micro element choices will vary from project to project depending on the particular requirements of the project. Furthermore, the analysis of case studies in chapter 3 (details are given in the appendix) have shown that it is necessary to go another step further in the decomposition of the element in some cases.

To illustrate this point, let us consider the Product Technology macro-element category. Product part (such as OPU housing) is the 1st level micro-element uncertainty under product technology based on the discussions in section 4.1. For this uncertainty, product part can be further decomposed into 2nd level micro-elements of supplier capability, supply chain and material property. The material property of the OPU housing can be further decomposed into 3rd level micro-elements of material thermal stability and design robustness for manufacturability as shown in figure 4.1.

The concept described in the above example of decomposing the macro-element into relevant micro-elements is similar to applying the concept of granularity on information.

> **Granularity is defined as the degree of modularity of a system. More granularity implies more flexibility in customizing a system, because there are more, smaller increments (granules) from which to choose. [McGraw-Hill, 2003]**
> **Hence Information Granularity is defined as the ability to break down a macro information element into micro information elements.**

The extent to which each macro-element is decomposed into micro-elements can logically go on indefinitely. However, the search must be limited as there is a finite amount of time, knowledge, attention or money to spend on a particular decision. There are many stopping rules to the activity of searching or decomposing the information. One approach is to implicitly calculate mentally the benefits and costs of searching for each further piece of information or uncertainty in this case and stop the search as soon as the costs outweigh the benefits [Anderson and Milson, 1989; Sargent, 1993]. [Gigerenzer, et al., 1999] have shown that there are simpler approaches called fast and frugal heuristics which employ a minimum of time, knowledge and computation to make adaptive choices in real environments. The relevant heuristic for uncertainty detection is the recognition heuristic whereby the decomposition of the macro-element stops once there are no more recognisable uncertainties.

This systematic process, which applies information granularity to decompose the relevant macro-elements into recognisable micro-elements that result in uncertainty, will enable the project team to detect more uncertainties depth-wise with full flexibility. This flexibility in selecting macro and micro elements is especially important in industries which are experiencing tremendous growth [TALC model of Moore, 1999]. The organisations or product development teams will undergo various changes through their business lifetime. This is also necessary in innovative product development organisations where there are a large number of factors that can be used to model the product innovation and thus the product uncertainty [Garcia and Calantone, 2002; Buijs and Valkenburg, 2005]. The exact choice of micro-elements is neither final nor fixed and depends very much on the ability to recognise the uncertainties [Gigerenzer, et al., 1999].

In summary, to meet the design requirement of completeness, the 1st building block of the proposed method should help the project team to review the macro-elements of uncertainty elements and then apply the concept of information granularity to decompose into micro-elements when necessary so that the second design requirement for flexibility is met. In carrying out this structured and systematic process of uncertainty analysis, the type 1 uncertainties could potentially be reduced as the project team will have an indication of the events or the failure mechanism (where the underlying probability of occurrence is still not known) that could result in potential reliability risks. While carrying out this process, if the project has all the required information to make risk analysis and assessments for a failure mechanism or event, they can identify the risks as well. Next we shall develop the building block to cater for type 2 uncertainty reductions.

### 5.1.3. Uncertainty Analysis using low resolution information

To make risk estimates, project teams traditionally need to have detailed ratio type of information as inputs if they are using currently available quality tools like FMEA, statistical tools or RQM. This would take even more time if the scope is made larger to encompass all possible uncertainties. As discussed in chapter 2, project teams in IPDP have insufficient time to collect the detailed ratio type of information. It was shown in section 4.2.2, that a counter intuitive design that uses low-resolution information in a structured manner can support in decision making. [Gigerenzer, et al., 1999] has shown that using simple or coarse information yields comparable results to traditional approaches of using detailed data and complex algorithms, especially when generalizing to new data. What is required now is to develop a structured method for uncertainty assessments using low-resolution information of nominal or ordinal type.

As we are dealing with RNIs, there will be many significant or innovative changes to the product or process. These changes may be known or unknown to the project team. Known changes are those in which the project team has detailed information regarding the micro-element that is changed or has all the required information to make an assessment. The project team must review each of the macro and micro-elements to determine which of them is known or unknown. For the known elements where the required information is available, it implies there is no uncertainty and hence can be classified as a risk. Risk assessment can then be done using the available quality tools. The unknown changes, where there are gaps in the required information, need to be marked for further action. This process of determining which of the elements is known or unknown makes up the first sub-step in this building block.

The unknown changes need to be analysed further to determine why there is no detailed information. The following classification will be used.

- A change that is totally new and there is no underlying information on the probability of occurrence, which can lead to Type 1 uncertainty
- A change that is not totally new but the project team has no detailed information or gaps in the required information, which can lead to Type 2 uncertainty
- A change that is not totally new, project team has information but it is not in a form that allows it to be used for traditional risk estimate computation, which can lead to Type 2 uncertainty

The information available on the above changes is classified as nominal information. The nominal information from situation (b) and (c) above is used to derive ordinal information by using comparative analysis. The ordinal information is then used for uncertainty assessment, which will be explained next. For totally new changes where there is no other nominal information to compare against, the change must be classified as uncertain until more information develops which reduces the uncertainty by providing at least an indication of the main parameters of the change.

The nominal information from the current project is compared with any available and relevant nominal information from past projects or from external sources to make a satisficing decision on the uncertainty. Using this approximate method, the project team can then judge whether the current nominal information is more (or less) uncertain compared to the past nominal information.

The above steps, of determining which elements are known or unknown, identifying type of nominal information and applying comparative analysis, form the 3rd building block for the new method. In this way low resolution information can be used for uncertainty assessment to derive an uncertainty estimate. This will potentially reduce Type 2 uncertainties. The next building block will address the process related requirements of proactiveness and details of how to use the new method in an IPDP.

### 5.1.4. Proactive use of new method

This requirement is not related to the detailed design of RQM-Lite but related to the way that this method should be used in product development. The above three method related building block proposals for completeness, flexibility and use of low resolution information identifies the elements where uncertainties may be present. In other words, this method will serve as a guide for the project team to determine which of the selected 3 macro elements categories (from the reference 12 categories) are uncertain and whether there is information available to do an uncertainty assessment when compared to an existing product. Once the uncertainties have been identified and managed, the potential risks related to the product reliability can then be analysed and identified. Using this method, valid statements can be made about the potential product reliability uncertainty and risks and thereby enable the project team to make more objective decisions related to the RNI reliability in the early phases of the IPDP.

As the new method requires low resolution information for identifying the uncertainties, it can be applied in the early phases of the IPDP, which is before the concept start milestone in the predictive phase. Through the application of the proposed method, actions will be initiated to reduce the information gaps and thus the uncertainty. The new information will then be used in the next iteration of the method and the whole process cycle will repeat. These iterations continue as the PDP progress until there is sufficient information available to reduce the selected macro-element uncertainty and hence risk for the RNI.

Using the three method related building blocks and the proposal on where to apply these building blocks in the PDP, the RQM-Lite method is proposed in the next section.

## 5.2. Design Proposal for Prototype Reliability and Quality Matrix (RQM) Lite

The objective of developing this new method is to aid the project team to proactively manage potential reliability problems including the aspects of uncertainty of RNI developed in IPDP by using low-resolution information.

### 5.2.1. RQM-Lite Process Steps

The proposed method is called the Reliability and Quality Matrix Lite (RQM-Lite) and consists of a 5 step process. The term RQM-Lite is used to indicate its ability to use low resolution information and is not a connotation of a simpler version of the RQM method.

| Step | Description | Purpose |
|---|---|---|
| 1 | Identify uncertainty macro-element category | Ensure the complete scope is addressed for Type 1 uncertainty analysis |
| 2 | Determine micro-elements | Ensure sufficient depth is addressed for Type 1 uncertainty analysis |
| 3 | Indicate the known or unknown elements | To carry out Type 1 uncertainty analysis |
| 4 | Determine information availability | To identify whether information is available for known element so that Type 2 uncertainty analysis |
| 5 | Estimate relative uncertainty (or risk based on available information) | To carry out Type 1 and 2 uncertainty assessment. |

*Table 5-1: The 5-step Process of RQM-Lite*

The above 5 steps of RQM-Lite can be carried out using low resolution information and hence the uncertainty analysis and assessment must start before the concept start milestone in the predictive phase in IPDP to fulfil the proactiveness requirements for the method

These steps however need not be performed in a sequential manner. Steps 1 and 2, which have been designed by using the 1st and 2nd building blocks to ensure completeness and flexibility can be finalised after a few rounds of discussion. Similarly, steps 3, 4 and 5 that have been designed using the 3rd building block to ensure the use of low-resolution information can be completed after a few rounds of discussion.

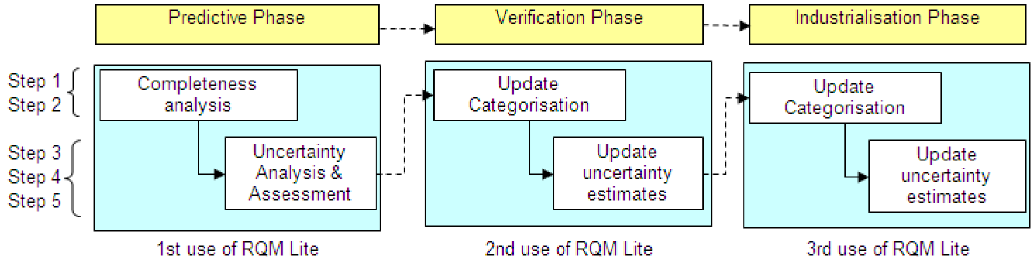


*Figure 5-1: The Process Flow for RQM-Lite*

Once the uncertainty related to the product reliability is identified after step 5, actions can then be initiated to reduce the uncertainty and thereafter carry out the risk management process. As more information is gathered, the 5 step process is repeated not only within the predictive phase but also throughout the remainder of the PDP. After the initial use of RQM-Lite during the predictive phase, it should be updated at least once during the verification and once during the industrialisation phase so that any learning can be used for future projects and also to review the effectiveness of satisficing decisions made on the choice of the macro and micro elements.

Each of the 5 steps is discussed in more detail in the next section.

### 5.2.2. Details of process

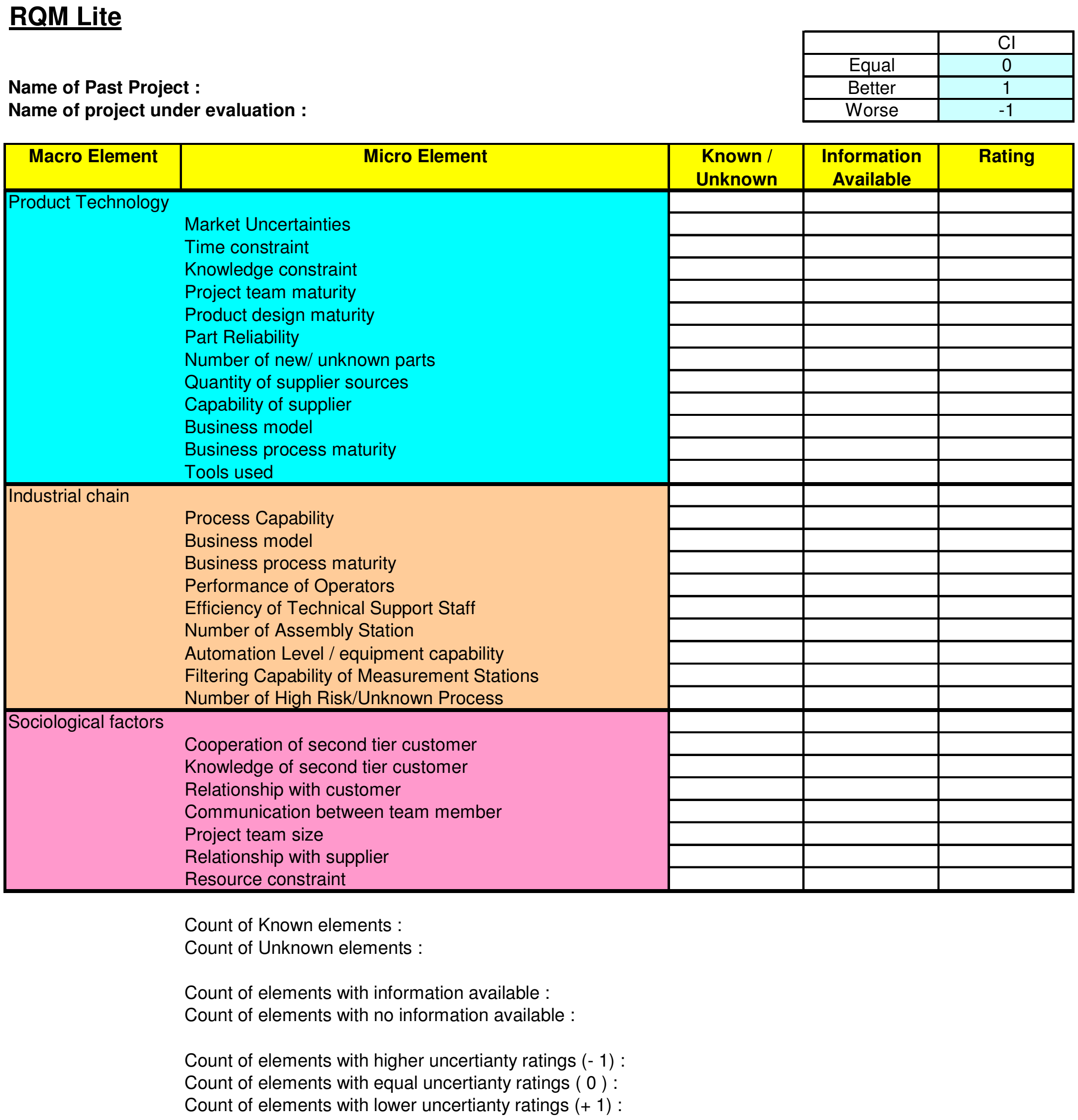
The design requirement for steps 1 and 2 is to ensure the completeness in scope analysis and flexibility in the choice of sub-elements. The project team should carry out a brainstorming session which gathers all the uncertainties for the development of the RNI, then work through the 12 macro-element categories mentioned earlier in this chapter along with any other company database (eg design rules, customer complaints, failure analysis, etc) as a further trigger for the brainstorming process to ensure a more effective (or better quality) uncertainty analysis. In the context of the

IPDP and the findings in section 4.2, the project team will need to make satisficing choices and focus on 3 (or at most 5) macro-element categories. The rest of the identified uncertainties need not be discarded completely but should be set aside for review at a later time when there are available resources.

Step 1: Identify Uncertainty Elements Category
Step 2: Determine micro-elements

Once the uncertainty macro-elements have been identified, it will be necessary to determine the micro-elements for each of the macro elements in step 2 by applying the concept of Information Granularity as mentioned in section 5.1.2. This process step is left as a flexible and open process as we are developing RNI. Dictating or laying a rigid framework may be counterproductive as some uncertainties due to new knowledge and experiences may not be covered by the original scope of the framework. Hence it is suggested that the responsibility and ownership for carrying out the RQM-Lite method lies with Project Manager, rather than the DQA department who is not a primary stakeholder in the development of the RNI. Thus it will be their objective and interest to ensure the method is applied correctly and with the right intent. The breaking down of the macro-elements into the relevant micro-level elements should be carried out in an iterative approach until all the required information that is necessary to make an uncertainty assessment is available.

The DQA department, who is independent, should serve as the facilitator to prevent opportunistic and/or incompetent actions as well as act as a moderating voice to ensure the project team does not go overboard. In order to structure the inputs collected for the RQM-Lite method, a spread-sheet based tool (Fig5.2) is proposed.



**RQM Lite**

| | CI |
|---|---|
| Equal | 0 |
| Better | 1 |
| Worse | -1 |

**Name of Past Project :**
**Name of project under evaluation :**

| Macro Element | Micro Element | Known / Unknown | Information Available | Rating |
|---|---|---|---|---|
| Product Technology | | | | |
| | Market Uncertainties | | | |
| | Time constraint | | | |
| | Knowledge constraint | | | |
| | Project team maturity | | | |
| | Product design maturity | | | |
| | Part Reliability | | | |
| | Number of new/ unknown parts | | | |
| | Quantity of supplier sources | | | |
| | Capability of supplier | | | |
| | Business model | | | |
| | Business process maturity | | | |
| | Tools used | | | |
| Industrial chain | | | | |
| | Process Capability | | | |
| | Business model | | | |
| | Business process maturity | | | |
| | Performance of Operators | | | |
| | Efficiency of Technical Support Staff | | | |
| | Number of Assembly Station | | | |
| | Automation Level / equipment capability | | | |
| | Filtering Capability of Measurement Stations | | | |
| | Number of High Risk/Unknown Process | | | |
| Sociological factors | | | | |
| | Cooperation of second tier customer | | | |
| | Knowledge of second tier customer | | | |
| | Relationship with customer | | | |
| | Communication between team member | | | |
| | Project team size | | | |
| | Relationship with supplier | | | |
| | Resource constraint | | | |

Count of Known elements :
Count of Unknown elements :

Count of elements with information available :
Count of elements with no information available :

Count of elements with higher uncertianty ratings (- 1) :
Count of elements with equal uncertianty ratings ( 0 ) :
Count of elements with lower uncertianty ratings (+ 1) :

*Figure 5-2 Reliability and Quality Matrix Lite (RQM-Lite) – Spreadsheet Based Tool*

The above steps 1 and 2 should ensure that all possible elements that will result in potential uncertainty are identified. The next steps will explain how to extend the analysis and start the uncertainty assessment.

Step 3 : Indicate the known and unknown elements
Step 4 : Determine information availability

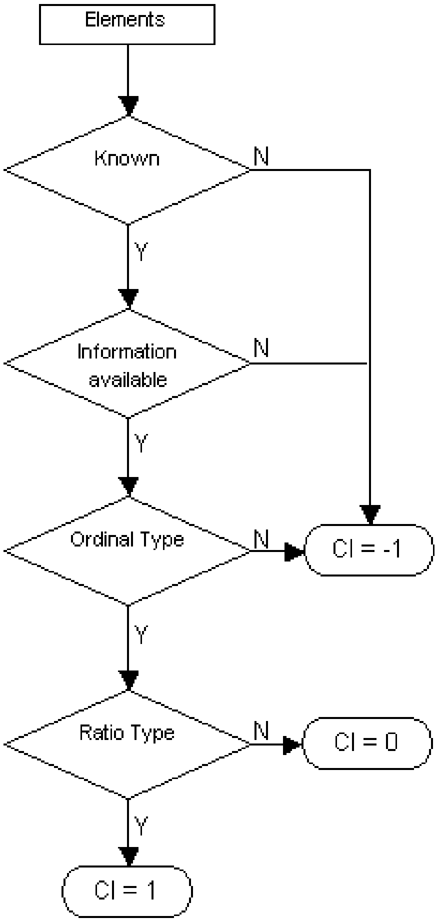
Step 3 and 4 are designed to guide the project team to estimate the level of uncertainty in the product using low resolution information. Having identified all the possible elements, a diversity analysis [Lu, 2002] is performed in step 3 to identify which of the macro and micro elements are known and unknown when compared to an existing or past product.

The unknown elements obviously have no high level information (neither ratio nor ordinal type information) to make as estimate of the underlying probability of occurrence of element. As such these elements are then rated as more uncertain when compared to a similar element from a past project.

The known elements can be described by information of different resolution levels and the next step will describe the design to indicate the uncertainty index level. Below is the flowchart used in step 4 to determine the uncertainty index level (CI).

$$CI = \begin{cases} -1 & \text{this uncertainty element is more uncertain in the new project compared with the past project} \\ 0 & \text{this uncertainty element has the same uncertainty level in the new project compared with the past project} \\ 1 & \text{this uncertainty element is less uncertain in the new project compared with the past project} \end{cases}$$

An element which is unknown will be rated as CI = -1, the default uncertainty index level where the element is more uncertain in the new project compared with the past project. Uncertainties from this element may potentially become type 1 uncertainties as shown in chapter 2. If the element is known but there is no information available to the project team it is also rated as CI = -1. Similar CI = -1 is rated for the element if the available information is nominal type. Both these cases may lead to potential type 2 uncertainties as shown in chapter 2.



If the element is known, the project team must determine whether they have sufficient information to make an uncertainty assessment. If the information available is of ratio type, then the uncertainty rating is lower (CI = 1) than past projects. In this case the uncertainty is insignificant and the potential risks can be analysed and assessed. If the information is available but is of nominal or ordinal type, the uncertainty rating is equal to past project (CI = 0) as there is a reference upon which the uncertainty assessment can be based on.

Step 5 : Estimate relative uncertainty

Once the available information is analysed, the uncertainty assessment will be carried out in step 5. The known elements with a CI which is equal or better than past projects will have uncertainty estimates that are based on past project performance results.

The unknown and known elements with CI lower than past projects will require further action to gather the required information to make uncertainty estimates. To reduce the information gaps, more iterations of the above 5 steps may be required for some events. By working through the RQM-Lite method, it provides useful insights into the potential reliability problems of the RNI and will result in a more objective reliability assessment. During the uncertainty assessment process, any estimates made will depend on the assumptions and hence it should not be the fault of the developer if a new phenomenon arises which is not allowed for in the assessment. However, the developer can be blamed if he has missed an event that is well established. As we are dealing with uncertainty and information gaps, the whole application of the method should be judged on the basis of a very 'good' attempt rather than in absolute terms [Ansell, 1992].

To assist in providing a clear overview of all the uncertainties for uncertainty management, the design should make a count of all the elements with negative, zero and positive CI as well as any risks estimated for zero and positive CI. In the situation where there are no elements with negative CI, it implies that the project team has all the required information to make risk analysis and assessments, hence little or negligible uncertainty. However, the project team will still need to be vigilant by repeating the 5 steps as the project progresses, for new uncertainties that may arise due to new information as the product is developed. Once the uncertainties have been identified and reduced, the project team will be able to make valid statements of the potential reliability risks.

The potential reliability risks can then be analysed, assessed and managed using the available quality tools mentioned in chapter 2. The use of the above method is not meant to replace all the other available tools, methods or processes that exist in the typical PDP, but should be seen as a complementary method to identify and manage the uncertainty of the RNI developed in IPDP. In this aspect, if there are uncertainties in the elements of product part or manufacturing process, the RQM method can be used for the uncertainty analysis and assessments. The resulting estimates and information derived from the RQM application can then be reflected in RQM-Lite. In the next section a comparison of RQM and RQM-Lite in terms of the strengths and weakness will be done.

## 5.3. RQM and RQM-Lite Strengths and Weaknesses Compared

Both RQM and RQM-Lite are methods that help the project team to reduce uncertainty and hence risks in order to proactively manage reliability in PDPs. Whilst RQM needs to have high resolution information (though it can be rough estimates) as inputs, RQM-Lite only requires low resolution information of ordinal type. The use of low resolution information enables the project team to apply RQM-Lite much earlier in the PDP process and within a much shorter time frame. It also enables a broader overview of all factors that may impact the product quality unlike in RQM method whose primary focus is on the product part and process factors. In this approach, RQM-Lite method is able to help the project team to reduce potential Type 1 and 2 uncertainties for RNI developed in IPDP.

Drawback of RQM-Lite is that it cannot be used as an absolute indicator of the uncertainty unlike RQM. This is due to the design that uses low resolution information. Ordinal type of information can only be derived by comparative analysis with another project. The uncertainty indications are relative to another project. This approach of using the collective views and experience is especially necessary in RNI being developed in IPDP as the underlying probabilities cannot be obtained due to the gaps in the required information.

As a result of the TTM pressure in consumer electronics industry, it is not possible to gather or process all of the necessary information required to make full analysis and assessments to arrive at a single figure. And compared to the other extreme of making instinctive guesses about the product reliability, a relative uncertainty indication provides more objectivity to make satisficing decisions for reliability management. [Gigerenzer, et al., 1999] has shown that simple heuristics with minimum information can perform comparably to more complex algorithms with detailed information, particularly when generalizing to new data, as is the case in IPDP.

Another aspect where RQM-Lite differs from RQM is the validation of their respective effectiveness. RQM can be applied using estimates from the early phase but the effectiveness of the uncertainty management can only be validated with high resolution information, which is a valid estimate as described in section 2.3 and 3.1. On the contrary the design of RQM-Lite requires the necessary outputs to be generated in the predictive phase itself. With these outputs, an indication can be derived to show whether it is able to guide the project team to identify more uncertainties when compared to RQM or any other method in a similar situation. Hence there is less dependency on whether the project has high resolution information.

Therefore RQM-Lite is designed to provide relative uncertainty indication using low resolution information so that reliability management decisions may be made with more objectivity at earlier phases of the PDP.

## 5.4. Conclusion

In this chapter, the RQM-Lite reliability management method for RNI is developed to identify uncertainties and thereby prevent potential reliability problems. The formal design requirements leading to design criteria were identified in chapter 4, and used here to develop the building blocks for the prototype design.

The first three building blocks cover the method related requirements. The first ensures the maximum coverage for uncertainty identification in IPDP. This is done by a top down approach for identifying the relevant macro-elements where potential uncertainties related to the product reliability may arise in the project. Next, information granularity is applied to enable sufficient depth of uncertainty identification for each of the macro-elements. The third building block defines how to carry out these activities using available low resolution information. The available nominal or ordinal information is used for comparative analysis with past products or projects to arrive at an uncertainty indication. These uncertainties need to be identified early enough in the PDP where there is optimum influence in the product design. The fourth building block defines the process related requirement to ensure that uncertainties are identified proactively in the predictive phase of the PDP. In this way, potential uncertainties and hence risks can be predicted and actions can be implemented in the product design itself to prevent potential reliability problems.

Based on the four building blocks, the design for new RQM-Lite method is proposed. A 5-step process is developed which guides the project team to identify the potential uncertainties in the macro and micro elements thereby reducing type 1 uncertainties. This is done by indicating which of these identified elements are known and unknown, whether there is low or high resolution information available and arriving at an uncertainty indication. With this the project team can then carry out further actions to first reduce uncertainties where they exist and then make risk predictions. As more information becomes available to the project team, the inputs are used to update the RQM-Lite for subsequent iterations.

RQM-Lite is similar to RQM in that it identifies and reduces uncertainty first before reducing risks. However it has a more complete scope, is structurally designed to identify micro elements when necessary and to use low resolution information. As a consequence, it provides only relative uncertainty indication when compared to a selected past product, unlike RQM which provides a numerical uncertainty and hence risk prediction. As such, in terms of the scope and use of low resolution information for the uncertainty management of RNI developed in IPDP, RQM-Lite is more suitable as compared to RQM.

In the next chapter, a first implementation of the prototype RQM-Lite design in an actual industrial environment is presented.

# CHAPTER 6 APPLICATION OF PROTOTYPE RQM-LITE IN INDUSTRY

This chapter presents the first implementation of the prototype RQM-Lite method in an industrial environment. It describes the constraints, evaluation approach and results of implementation. The findings will provide an insight into whether the prototype design meets the research objective and has potential for further refinement.

In section 6.1, the evaluation approach to demonstrate the validity of the RQM-Lite design criteria is outlined. A first implementation using case studies is covered in section 6.2 with a discussion of the results in section 6.3. This is followed by a reflection on the implementation in section 6.4 and the results in section 6.5.

## 6.1. Evaluation approach of proposed RQM-Lite design

Ideally, when evaluating RQM-Lite, the method should be applied to one RNI project in the field and used accordingly as intended for the entire PDP. However due to the inherent aspect of inductive research in a business setting that is operating in an innovative and dynamic environment, it is not really possible to foresee how this type of project would proceed beforehand. Therefore, it was decided to apply RQM-Lite to a number of RNI projects, all situated in the consumer electronics industry. The data richness from the multiple micro-elements under analysis should ensure internal validity while the similar structure of the PDP in OC compared to the other companies operating in the same industry (as shown in chapter 3) should ensure that the findings can be generalized to the industry and thereby ensure external validity to the industry.

The RQM-Lite implementation is done by following the 5-step process for RQM-Lite as described in section 5.2. A short briefing is given to the product manager of the project on the purpose of the method and how to fill the spreadsheet based tool, which serves as an aid to consolidate the collected information. The RQM-Lite spreadsheet from the case studies is analysed to confirm if design proposal meets the four design criteria described in section 4.3.

**Proactiveness – It should be used in the predictive phase**

\+ Used during the predictive phase

-- Not used during the predictive phase

**Completeness – Scope which covers the total project**

\+ Scope covers the total product development project

-- Scope is limited to product parts and process development

**Flexibility – Able to select the macro elements and decompose them into micro-elements**

\+ Able to select uncertainty macro-elements and decompose it to micro-elements

-- Unable to select uncertainty macro-elements or decompose it to micro-elements

**Information type – Able to use low resolution information**

\+ Use low resolution information

-- Use high resolution information

If all the above criteria are met, i.e. all the four criteria have a positive rating, it indicates that the design is able to guide the project team to identify uncertainty first so that risk reduction can be done next.

Content wise, the information generated in each case study during the first use of the RQM-Lite in the predictive phase should provide an indication of the uncertainties and the completed spreadsheet would summarise the uncertainties identified as follows.

Count of elements with higher uncertianty ratings (- 1) :
Count of elements with equal uncertianty ratings ( 0 ) :
Count of elements with lower uncertianty ratings (+ 1) :

This summary would serve as the basis for uncertainty and hence risk management activities to be initiated. In the situation where uncertainties have been identified, thus allowing it to be managed, would mean that the prototype RQM-Lite design method is effective and hence the identified design criteria for the method are valid.

If no uncertainties are identified, there are two possibilities. First there are no uncertainties in the required information to predict the product reliability and this is further validated when the product development is allowed to continue and the industrial data confirms there is no uncertainties. Secondly, there are uncertainties, but the instrument is ineffective in identifying the uncertainties. In this situation, the product development continues and the industrial data that is obtained later indicates unidentified uncertainties and hence unpredicted risks. In the latter situation, the design criteria are not valid and further analysis will need to be done.

It must be highlighted that the objective of this research is to identify the design criteria for a suitable method that can be used to manage product reliability, especially the uncertainty aspects for RNI developed in an IPDP and as such it is not the main intent to develop a tool or method. The RQM-Lite method is developed more as a means to validate the design criteria. The case study evaluations will thus focus on the four design criteria from a process perspective. Furthermore, it has been shown in chapter 5 that the uncertainty indication should be viewed more as a relative indication rather than an absolute value. In this aspect, the efficacy and efficiency of the design criteria will be evaluated through interviews carried out with the key project team members.

## 6.2. First Implementation

To validate the design criteria a multiple case study approach was used. The industrial cases that were selected for the implementation are described next.

### 6.2.1. Case selection and description

The case studies for the first implementation must be selected based on the same requirements described in section 3.3, in that the IPDP should be representative of IPDP in the consumer electronics industry. The type of product being developed should be a RNI and there must be accessibility to the project team members as well as project and company data.

Next, the RQM Implementation should be facilitated by a qualified facilitator, whose role is not just a moderator but is able to guide the project team in applying the RQM-Lite method correctly and is sufficiently competent to verify the analysis and assessments done by the project team in relation to the RNI uncertainties and risks. As the RQM-Lite method is similar to RQM in that it aims to help identify uncertainties related to product reliability, a person who has been qualified as an RQM facilitator is also suitable to facilitate the RQM-Lite method from a technical competency standpoint. However, as this is a new method meant for application on RNI and is also a first implementation, the facilitators will need to be trained directly by the developer of the method on the application process and work under the supervision of the RQM-Lite developer until he is approved by the RQM-Lite developer to work independently. The facilitator should also have independence and freedom from bias, in terms of responsibility (to the organisation and presenting an accurate yet neutral overview of the uncertainties and risks) and accountability (to the project team for consolidating the inputs). The subsequent facilitator qualifications will be based on the same approach mentioned in section 3.1. As this is a first implementation, the detailed guidelines to be used will be based on the 5 step process outlined in the previous chapter, which will be refined as the case study progresses.

Lastly, to ensure the deployment and usage of the method is done correctly, there must be commitment from the organisation to implement and evaluate the method. Summarising the case selection criteria:

- The structure of the IPDP is similar to IPDP in the consumer electronics industry
- Product that is being developed must be a RNI
- Accessibility to the project team and data
- Implementation of RQM-Lite method must be facilitated
- There is commitment from the project team to apply the method

Based on the above criteria, the cases for implementation were selected from OC, as their IPDP is similar to IPDP in consumer electronics industry [Philips, 1994; Clausing, 1994; PDMA, 2004]. In each case study, a qualified RQM facilitator from the DQA department is assigned full time to the project team after he has been trained by the developer of RQM-Lite method. By being part of the project team, it ensures that the facilitator has full accessibility to the project data and can carry out interviews with the necessary project team members. Finally, the project team who are currently using RQM have reaffirmed their commitment to apply the new RQM-Lite method.

Three new cases are selected, namely OPU86[4], OPU66 and OPU76. A brief description is given below on why they are classified as RNI and are suitable for the first implementation, with more details covered in appendix D.

OPU66 was a project that was initiated in the company to enter the automotive OPU segment. This project can be considered as a micro level marketing discontinuity as the end product is not new to the automotive customers though it is the first time the company is developing an OPU for automotive specifications. As the specifications for automotive industry are much more severe or demanding, it would entail the use of new parts with higher tolerances and new architecture, hence a macro level discontinuity. This is to ensure that the design performance can withstand the more

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[4] The project codes in this thesis refer to internal company information which is confidential, but the author had full access and received full permission to use it in the context of this thesis

severe operational environments that a car may need to endure as compared to an audio video player in a stable home environment. Using the classification scheme by [Garcia and Calantone, 2001], this product would be classified as a RNI.

OPU86 was another project initiated to enter the notebook market segment which is new for the company. The new slim form factor would require totally new parts and a new platform architecture to realize the required miniaturization of the OPU. The project team that was put together to realize this product was from two different sites and backgrounds. This would require many creative ways of working together to be developed. This micro level marketing discontinuity along with the macro level technological discontinuity would place it as a RNI

The third case is the OPU76 which is a project that is done by a new project team that had ‘read only’ OPU product knowledge and experience. The project team had two very difficult objectives. First a drastic cost down target and secondly, increased customer requirements that represent a micro level marketing discontinuity. To meet both these targets in a short time frame would require a total redesign of the any existing OPU in the company in order to reduce the component count, hence representing a macro level technological discontinuity. Hence this project is also classified as a RNI.

### 6.2.2. Implementation Strategy

The RQM-Lite method ideally needs to be applied before the concept start milestone in the predictive phase based on the process related requirements described in section 5.1 and 5.2. A short briefing on the purpose of the RQM-Lite method must be given to the product manager and project team members who will be applying the method. The RQM-Lite method sessions need to be facilitated by a trained facilitator (as mentioned in the previous section) to ensure the method is applied correctly.

RQM-Lite: Steps 1 & 2

In these steps, uncertainty analysis is carried out to identify the macro and micro uncertainty elements that are relevant to the RNI. The details for this process are described in section 5.2, where the project manager will work through the 12 macro element categories [Keizer, et al., 2002] along with any other company lists (eg design rules, customer complaints, failure analysis, etc) that are available as a trigger for the uncertainty elements selection. Once the macro uncertainty elements are identified, the same process is applied to determine the relevant micro uncertainty elements by applying the concept of information granularity. This decomposition process will need to be carried out to as many sub levels as required until there is sufficient level of detail that is useful for the project, taking into consideration the satisficing principle of [Simon, 1976].

Inputs for the above process are provided by the respective subject matter experts where required. For example, the product manager who has the customer needs and knows the business needs can decide on the product family, brand positioning, consumer acceptance, trade customer, commercial viability and public acceptance elements.

RQM-Lite: Steps 3 & 4

The uncertainty analysis is further continued in these steps. The project manager with the inputs from the project team will identify which elements have gaps in information and label these as unknowns and give a CI rating of -1. The known elements will be then be analysed using the detailed process in section 5.2 and based on the availability of the required information, assign CI ratings of -1, 0 or 1.

RQM-Lite: Step 5

The project team will then carry out the uncertainty assessment to make an uncertainty estimate for the element. How the uncertainty assessment can be carried out is explained in section 5.2. Several iterations may be required to gather information in order to reduce the information gap, hence reducing the uncertainty in the information used to make estimates about the probability of occurrence of the potential failure mechanisms or event. By the end of this step, the main macro and micro uncertainty elements that are significant (based on satisficing decision making approach) to identify uncertainty related to the product reliability would be listed down along with a relative indication of the uncertainty, in terms of the probability of occurrence. This overview will indicate where the uncertainties are in terms of the information gaps, which if reduced, would enable the project team to make risk estimates with certainty.

Several iterations of the 5-step process may be required and at the minimum one cycle must be done for each of the predictive, verification and industrialization phases. The subsequent cycles serve several purposes. First to enable new uncertainties that may occur due to changing customer or business needs, to be identified. Second, as a source of learning for other projects.

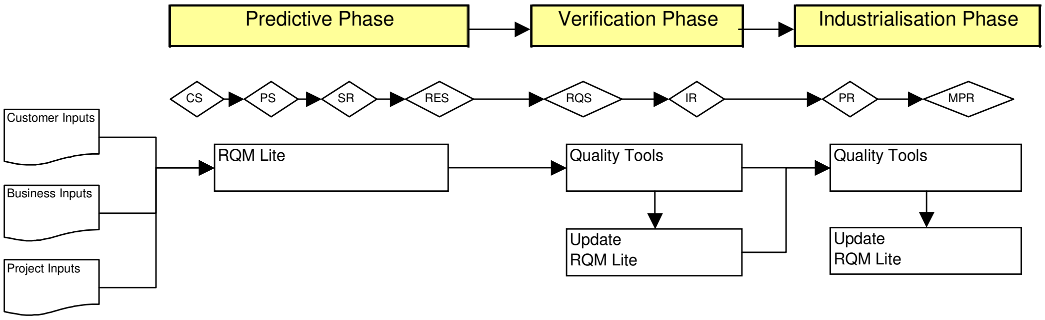

*Figure 6-1: RQM-Lite Integration with Existing Quality Tools in the Product Development Process*

The uncertainty management thus requires the gathering of information to reduce the information gaps so that the probability of occurrence for an event or failure mechanism can specified with certainty, hence resulting in risk estimates. Then further risk analysis, assessments and management can be executed using the existing tools such as RQM, FMEA, DOE and simulation tools.

## 6.3. Implementation Results

The case study results after consolidation and analysis, were cross checked with other sources of information (project data, customer data, design rules, FMEAs, risk assessments, etc) in the company and through informal interviews with product managers, project managers and project team members in OC.

### Proactive usage of RQM-Lite

During the application of RQM-Lite in the 3 cases, all the 5 steps mentioned in section 5.2 were applied in the predictive phase.

| | **OPU86** | **OPU66** | **OPU76** |
|---|---|---|---|
| Usage of RQM-Lite during each phase | | | |
| Predictive phase | Yes | Yes | Yes |
| Verification phase | Yes | No | Yes |
| Industrialisation phase | No | No | No |

*Table 6-1: Usage of RQM-Lite at Each Phase of the PDP*

### Uncertainty Macro Elements and Micro Elements

In the three cases, the product managers reviewed and selected the three macro-element categories for uncertainty: Product Technology, Manufacturing Technology and Organizational & Project Management. In the OPU86 case, the product manager found the elements were too general given the information available to him at that point and thus wanted to have a more detailed categorization. The concept of information granularity was applied to further decompose the macro element in terms of micro elements as shown below.

| | |
|---|---|
| Product Technology | Market Uncertainties |
| | Time constraint |
| | Knowledge constraint |
| | Project team maturity |
| | Product design maturity |
| | Part Reliability |
| | Number of new/ unknown parts |
| | Quantity of supplier sources |
| | Capability of supplier |
| | Business model |
| | Business process maturity |
| | Tools used |
| Manufacturing Technology | Process Capability |
| | Business model |
| | Business process maturity |
| | Performance of Operators |
| | Efficiency of Technical Support Staff |
| | Number of Assembly Station |
| | Automation Level / equipment capability |
| | Filtering Capability of Measurement Stations |
| | Number of High Risk/Unknown Process |
| Organization & Project Management | Cooperation of second tier customer |
| | Knowledge of second tier customer |
| | Relationship with customer |
| | Communication between team member |
| | Project team size |
| | Relationship with supplier |
| | Resource constraint |

*Table 6-2: Macro and Micro Element Categorization*

In OPU66, the product manager did not further subdivide the three macro elements as the project was in its preliminary stage and no project team had been put together for preliminary concept studies yet. Furthermore, the organization had yet to decide if they wanted to include this range of products in its business portfolio. In OPU76, the product manager was very clear in what the changes were for the project team and hence did not need to further decompose the macro-elements.

The product managers then indicated known / unknown status, availability of information and uncertainty indication for each of the macro and micro elements. The summarized results for each step in each of the three cases are tabulated in table 6.4 below. The details can be found in appendix D.

| | OPU86 | OPU66 | OPU76 |
|---|---|---|---|
| Completeness | | | |
| 1. Uncertainty macro element category | Product Technology<br>Manufacturing Technology<br>Organization & Project Management | Product Technology<br>Manufacturing Technology<br>Organization & Project Management | Product Technology<br>Manufacturing Technology<br>Organization & Project Management |
| Flexibility in Categorisation | | | |
| 2. Uncertainty micro elements (information granularity) | Yes | Yes | Yes |

*Table 6-3: Overview of RQM-Lite Results for Steps 1 and 2*

The above two process steps ensured the maximum breadth and depth for uncertainty identification given the constraints of the RNI being developed in an IPDP. This fulfils the criteria of completeness that was identified in chapter 4. Next we shall present the results from steps 3 to 5.

### Uncertainty Analysis

In OPU86 the unknown elements were related to the customer relationship, cooperation and knowledge micro elements under the Organization & Project Management macro element. The miniaturization of product which included the micro-elements of new parts to be used, product design maturity and business model was unknown. As new parts and product architecture are introduced, new innovative processes will also be required to be developed and is thus an unknown element. In OPU76 the product technology that was needed to realize the breakthrough in cost reductions required the use of a new and innovative dual wavelength laser that was new to the industry and hence unknown to the project team. In OPU66, all the three macro-elements were unknown to the project team. All of these identified unknown elements for each project were rated with an uncertainty rating of CI = –1 indicating that the uncertainty level for each element is much worse than a similar element from a past project.

The next process step was to determine the information availability for the known elements. Of the remaining known elements in the three cases, only one element in OPU86 had no available information with the project team. This was the element of market information, which was known in the industry and known at a strategic level to the organization, but was not available in a usable form to the project team. Hence this was given an uncertainty rating of CI = –1.

Based on the available information type for the remaining known elements, the ratings were assigned for each element. The elements that were described by nominal information had an uncertainty rating of CI = –1, while those described by ordinal information had an uncertainty rating of CI = 0 and the ratio based elements had an uncertainty rating of CI = +1. These ratings give a measure of the level of uncertainty present in these ratings. The elements with high uncertainty then need to have actions initiated in order to reduce the rating from CI = –1 to CI = 0 or +1. Those with ratings of CI = 0 and CI = +1 indicate that there is sufficient information to make estimates using certain information, hence risk management activities can be initiated using the standard quality tools that are available. The resulting output from the risk management activities need to be used to update the RQM-Lite method until all the elements have a CI rating of 0 or +1.

In the OPU86 case, where the customer related elements had the CI = –1 uncertainty ratings, the project initiated a series of actions such as having a key account team targeted at two potential customers (BXXX and QXX) and having high level management engagement with the preferred customer on joint product roadmaps. This reduced the uncertainty from CI = –1 to CI = 0 for the customer related uncertainty elements. On the uncertainty regarding the choice of chipset to be used with OPU86, technical teams were sent to the selected chipset maker and assurances were given to the chipset maker that the project team was working with a potential customer. This reduced the uncertainty to CI = 0. This approach also helped to surface more information regarding the business model for the OPU86, thus reducing the uncertainty rating from CI = –1 to CI = +1.

On the basis of higher uncertainty in all three macro elements in the OPU66 project as well as large investments required for the project, the product manager discussed with the business management whether further work should proceed to reduce the uncertainties. In view of the fact that product technology element (which includes more stringent customer requirements) was highly uncertain and there was no committed customer willing to continue with the project, the OPU66 project was stopped.

In OPU76, it was found that 67% of the elements at the total project level were of equal or lower uncertainty compared to a past project. This was mainly due to the OPU design which was designed for manufacturability by reducing the number of process steps required to assemble the product and simplifying some of the assembly actions to reduce the dependency on the operator skill. The equipment capability to manufacture this OPU had been improved in a concurrent activity that was initiated by the Equipment Engineering department based on learning from previous projects. The equipment group had used early prototypes of the OPU to test and validate the equipment capability, hence reducing the uncertainty related to equipment gage. The only high uncertainty aspect was from the macro element of product technology, due to the new product and component designs. Here the product manager and project team initiated several measures to reduce the uncertainties by gathering more information through early prototypes and hence ensure the risk was within acceptable limits to both OC and the customer. The additional information resulted in clearer customer requirements and less uncertainty related to Dual Wavelength laser and overall product technology. In this approach of proactively identifying the uncertainties in the early phases by using low resolution information, the project team is able to overcome potential product reliability problems by incorporating the solutions into the design.

In OPU86, there were 12 elements where the uncertainties were higher. As actions had been put in place to reduce some of these critical elements as explained above and the fact that there was 19 elements with equal or lower uncertainties, the project was approved to proceed to the product development phase. The project was provided with the additional resources directly and in a supporting role to take the necessary actions to reduce these uncertainties. In order to monitor the iterative activities under TTM pressure, several additional management review milestones were added in between the standard PDP milestones. The above findings are summarised in the table below.

| | **OPU86** | **OPU66** | **OPU76** |
|---|---|---|---|
| Uncertainty Analysis using low resolution information | | | |
| 3. Indicate Known / Unknown for each element | | | |
| Known elements | 22 | 0 | 2 |
| Unknown elements | 9 | 3 | 1 |
| 4. Determine information availability for each element | | | |
| Available (Yes) | 21 | 0 | 2 |
| Not Available (No) | 10 | 3 | 1 |
| 5. Estimate relative risk for each element | | | |
| Uncertainty is better (CI = +1) | 6 | 0 | 0 |
| Uncertainty is equal (CI = 0) | 13 | 0 | 2 |
| Uncertainty is worse (CI = -1) | 12 | 3 | 1 |

*Table 6-4: Overview of RQM-Lite Results for Steps 3 to 5*

### 6.3.1. Analysed Results

The objective of this research is to develop the design criteria for a method that helps to manage product reliability uncertainties and hence risks for RNI. The RQM-Lite method was developed to validate the design criteria of proactiveness, completeness, flexibility and ability to use low resolution information. This method is intended to help identify uncertainties, thereby allowing the project team to take preventive actions to improve the product reliability proactively in IPDP. The implementation of the prototype RQM-Lite method in three case studies was done to demonstrate the validity of the design criteria. The results from section 6.3 are summarised below based on the design criteria.

| | **OPU86** | **OPU66** | **OPU76** |
|---|---|---|---|
| Design criteria | | | |
| Proactiveness | + | + | + |
| Completeness | + | + | + |
| Flexibility | + | + | + |
| Information type | + | + | + |

This demonstrates that process wise, the RQM-Lite method is able to guide the project team to identify uncertainties so that they can manage the product quality and reliability. Next, the effectiveness of the RQM-Lite method in terms of content will be discussed.

In all three industrial case studies in which RQM-Lite method was implemented, the uncertainty identification through the review of elements was carried out in the predictive phase. The product managers selected the macro elements of Product Technology, Manufacturing Technology and Organization & Project Management. Only in one project, OPU86, the product manager wanted to decompose the macro-element categories further into micro-elements to aid in his uncertainty analysis and assessment as he had high uncertainty elements. OPU66 also had high uncertainty elements, but the project was stopped in view that the customer related uncertainties could not be reduced as there was no committed customer interested in the product development. On the other hand, the OPU76 project team had the required information from early prototypes to assess the uncertainty and hence did not need to increase the information granularity.

In order to reduce the subjectivity and bias of the above evaluation as well as to provide a better quality of comparison to RQM, it would be ideal if formal anonymous evaluations can be carried out among all the team members that participated during the case studies. However, as the project teams were under TTM pressure, they preferred to provide their feedback through a direct interview rather than take time to fill up a survey questionnaire. Any bias in the opinions or feedback, if it exists, would not be in favour of the new RQM-Lite method as its usage in actual projects would imply extra work and additional training for the project team. The feedback would be rated as positive only if there is considerable added value in spite of the extra efforts and learning curve involved.

Extracts from the evaluation questions and feedback is tabled and discussed below as well as in the next section, while the actual details are consolidated in the appendix. One product manager gave the feedback that the RQM-Lite method “locks in all potential risks”. As the implementation of RQM-Lite was done in RNI at the early predictive phase, there was no high resolution information available for the elements in each of the projects. The product managers only had low resolution information which they used in the structured framework provided by the RQM-Lite method. This process enabled the product managers to identify the known / unknown elements, check the availability of nominal type information and then derive the ordinal information. With this ordinal information, they were able to indicate the uncertainty level for each of the elements. By identifying these potential uncertainties in the predictive phase, the project team is then able to proactively implement actions to reduce the uncertainties and hence potential risks.

| Evaluation Question<br>How does this method compare with existing methods for uncertainty management of product reliability ?<br>Any other feedback ? |
|---|
| Response<br>OPU76<br>1. Used objectively, it is useful<br>2. Use the index as an indicator and with some maturity, not as an absolute<br><br>OPU86<br>1. The number (count of uncertainty elements) is dangerous as it is taken by top mgmt as final committed number<br>2. It is frequently forgotten under what assumptions and information set it was based on<br>3. Useful to identify quickly the weak areas<br>4. Useful to track own progress (in terms of count of uncertainty elements)<br>5. Useful to highlight uncertainties and high level project risks<br><br>OPU66<br>1. This only serves as a background framework to highlight risks (uncertainty)<br>2. This is more systematic than project maturity grid to provide a more comprehensive risk (uncertainty) estimate<br>3. Regardless of team openness, this is more comprehensive and locks all potential risks (uncertainty) |

As there was no detailed checklist requiring high resolution information, the project managers were not overwhelmed by the method nor stuck while consolidating high resolution information as was the case in applying RQM (as shown in chapter 3). This visibility and quick overview enabled the product managers and project team to gather the necessary low resolution information required to reduce the uncertainty. In this process, the project team was able to identify and then reduce the potential uncertainties that otherwise may not be addressed in RNI that is developed at OC with the existing RQM method.

| | **OPU86** | **OPU66** | **OPU76** |
|---|---|---|---|
| RQM-Lite vs. RQM | | | |
| Able to detect more uncertainties | Yes | Yes | Yes |
| RQM-Lite is effective (content wise) | Yes | Yes | Yes |

More about the feedback is discussed in the next section. To summarise, all three project responses indicate that they preferred the RQM-Lite method for uncertainty management in RNI.

## 6.4. Reflection on the findings

The first implementation on 3 case studies was well received by the product managers who used it. The OPU86 project manager found that the structured RQM-Lite method and supporting spreadsheet tool provided a framework for identifying uncertainties and also recording down the “assumptions under which the information” was based upon. It is more complete in its scope as it was able to highlight more uncertainty elements (Table 6.4) as was shown in the three case studies.

The RQM-Lite method is able to use low resolution information as inputs. This enables it to be used in the early phases of IPDP where decisions have to be made based on available nominal and ordinal information. Discussions with the product managers and project team revealed that they were less overwhelmed with the method when compared to RQM and that it helped them identify very quickly (RQM-Lite method required half the time compared to RQM) the uncertainties at a broad or high level. This feedback was validated by the number of uncertainties identified (Table 6.4).

Another feedback from the OPU76 product manager was that the uncertainties identified by using the RQM-Lite method should be used as an indicator of the potential weak areas in the product reliability and not as an absolute number for comparison across different projects. This remark is valid as the uncertainty indications are referenced to past projects and uses ordinal information. As the uncertainties are not based on ratio type of information, the number of uncertainties surfaced cannot be used as a target for project teams to aim for nor for project performance comparisons. These uncertainty indications provide a more objective method to aid in decision making and reliability management during the early phases of the RNI developed in IPDP.

Furthermore this approach of using low resolution information in a simple logical model rather than applying complex statistics is sufficiently robust for making predictions for new data or radical product development. This is explained by the phenomenon known as over fitting (Geman et al., 1992; Massaro, 1988), which stems from assuming that every detail is of utmost relevance. Thus, the important difference between fitting and generalization is, fitting attempts to model decisions for a given set of data while generalization predicts or infers based on new data. In fitting, it is usually true that the more parameters a model has, and the more information (cues) it uses, the better it will fit given data. This situation is more applicable in derivative PDP. In generalization, in contrast, more is not necessarily better. A computationally simple strategy that uses only some of the available information can be more robust [Gigerenzer, et al., 1999], making more accurate predictions for new data, than a computationally complex, information-guzzling strategy that over fits.

Although the RQM-Lite method was applied in the same company as the industrial case studies in chapter 3 (to reduce the influence of unplanned disturbances), it does not mean that it can only be used in this company. It is possible to use the RQM-Lite method in other companies that have PDP that are structurally similar to the IPDP under research and in similar industries dealing with RNI development in consumer electronics industry. This is possible according to the case studies reported in [Brombacher, et al., 2001] where the business processes and technology used in the company under research is not very different from other companies in the similar industry. Hence the results from this first application can be generalized to be applicable to the industry.

## 6.5. Conclusion

The first implementation of RQM-Lite method in three new case studies in an actual industrial environment show that the case study results are positive and the proposed design criteria are valid. It encourages the further refinement of the RQM-Lite method for use in a broader range of companies, which is possible according to [Brombacher, et al., 2001]. The effectiveness of uncertainty management in projects was proven in all three cases as more uncertainties were identified in all areas, besides product parts and process.

It is thus possible to define a method based on the design criteria to manage uncertainty related to reliability of RNI developed in IPDP using low resolution information.

# CHAPTER 7 CONCLUSION AND FUTURE RESEARCH

To conclude this research thesis the major research findings are summarised in section 7.1 with respect to the research problem, proposition and questions identified in chapter 1. Section 7.2 evaluates this research, discusses the contributions made and the generalisations of the research. The limitations of the research and future research directions are proposed in section 7.3.

## 7.1. Summary of the Research

This thesis is a follow up research on the prior work done by [Lu, 2002]. It extends the research of uncertainty aspects of reliability management of concurrent fast PDP (CFPDP) to the Iterative Product Development Process (IPDP) operating in a consumer electronics industry that is characterised by increasing product complexity, a more global economy, shorter TTM and decreasing tolerance of customers for quality problems (as discussed in chapter 1).

The combination of the four conflicting industry characteristics mentioned above requires businesses to shift their portfolio towards more innovative products with inherently higher uncertainty. The traditional reliability methods cannot cope with these uncertainties in Really New Innovation (RNI) that are developed in IPDP. In the context of this research, there is a need to find out how to manage the uncertainty and risk, in terms of the probability of occurrence of a potential failure mechanism or event, which affects the reliability information of RNI developed in IPDP.

[Lu, 2002] developed the RQM Method to help manage the uncertainties and risk in product reliability in CFPDP. The research proposition is thus defined as:

**Research Proposition: Since RQM can be used to manage the uncertainty aspect of reliability information flows in CFPDP, it can similarly be used for RNI in IPDP.**

As RNI developed in IPDP are more innovative than derivative products, there are more uncertainties related to the reliability information. This leads to the first research question.

**Research question 1: How effectively can risk and uncertainty aspects of reliability be managed for RNI developed in IPDP using the RQM method?**

It was expected that the research findings would also describe the challenges and activities faced by actual project teams in the field.

If the RQM method is found to be effective, it is necessary to identify the influencing design criteria that can be used to further improve the RQM method; otherwise it can be used as the design criteria for a new method to manage the reliability of RNI in IPDP.

**Research question 2: What are the design criteria that can be used to manage risk and uncertainty aspects of reliability of RNI being developed in IPDP?**

By identifying these design criteria, it should serve as the basis for developing a broader and more comprehensive method that can help achieve the research objective.

**Research Objective: To identify the design criteria for a method that can be used to manage reliability, especially the risk and uncertainty aspects, of RNI in an IPDP.**

Three evaluation criteria were developed to test the proposition, namely proactive management, effective uncertainty management and effective risk management. Based on these criteria, RQM was applied on two case studies from the industry where a RNI was developed in an IPDP. The two industrial case study analyses showed that

- RQM was unable to help identify the uncertainty (Type 1) in RNI as it explicitly focuses on the product parts and production processes. Uncertainties arising from the other areas, which are left to the developer discretion, were not identified due to project constraints.
- RQM could not be used to accurately quantify the identified uncertainty (Type 2) in RNI. Though the project team was able to correctly identify the potential uncertainty through uncertainty analysis, they did not have the required information for uncertainty assessment either due to a lack of the required information in the project team or lack of priority to estimate the uncertainty.

These findings show that despite the proven effectiveness of RQM method when it is used for uncertainty management in derivative product development in CFPDP (which is the original intent of the RQM method), its application ‘as is’ could not be extended to RNI that is developed in an IPDP. The RNI projects require, at the minimum, uncertainty estimates to be made using low resolution information that is relative or comparative in nature in the early phases of the IPDP. This differs significantly from the derivative projects that require high resolution information (which could be rough or validated estimates). It was concluded that RQM was unable to effectively manage uncertainty in RNI developed in IPDP, thereby answering research question 1. Thus the research proposition could not hold all the time.

As the research objective was not to adapt or refine the RQM method but instead to define the design criteria, the above findings led to the development of the design requirements and criteria that are suitable for a method that can help manage uncertainty and risk in RNI.

The four design criteria that are defined and answer the research question 2 are:

- Proactiveness – It should be used in the predictive phase
- Completeness – Scope which covers a wider scope of uncertainty in the total project
- Flexibility – Ability to select the macro elements and decompose them into micro-elements
- Information type – Ability to use low resolution information

In order to demonstrate the validity of the above design criteria, a prototype method called Reliability & Quality Matrix Lite (RQM-Lite) was proposed and implemented in three industrial case studies for RNI developed in IPDP. The term RQM-Lite is used to indicate its ability to use low resolution information and is not a connotation of a simpler version of the RQM method.

It was found that the RQM-Lite method helped to identify uncertainties (Type 1) in areas other than the product parts and process, in other words more completely when compared with the RQM method. The product managers were able to use the nominal and ordinal information (low resolution information) when applying RQM-Lite method for uncertainty analysis in the early phases of the IPDP. By applying the concept of information granularity, they were able to decompose the selected macro-elements into finer micro-elements.

In view of achieving an “acceptable level of uncertainty, hence risk” to make satisficing decisions in the early phases of the IPDP, a relative uncertainty indication is used rather than an absolute value in the RQM-Lite method. The uncertainty assessment steps were done by comparing each and every identified macro (or micro) element in the current project with selected past projects to obtain a relative uncertainty indication. The RQM-Lite method along with the supporting spreadsheet tool provides a framework for gathering the required information to reduce the information gaps. Once the required information is obtained, it implies there is low uncertainty (Type 2); hence valid statements can be made about the risk in terms of the probability of occurrence for the element or failure mechanism.

This process of uncertainty analysis, assessment and reduction by reducing the information gaps is done first so that the risk management process can be done with more certainty. By this RQM-Lite method, the identified design criteria have been used to help the project team to manage the uncertainty and risk aspects of the reliability of the RNI developed in an IPDP, thereby achieving the research objective.

## 7.2. Research Evaluation

### 7.2.1. Main Contributions

The three main contributions made by this thesis are summarised below. The RQM method was observed to be effective when it was used for managing uncertainties in the derivative products in CFPDP, however its effectiveness was limited when managing uncertainties in RNI that is developed in IPDP. Hence, it was concluded that RQM method could not be applied directly, as it is, to help manage uncertainties in RNI developed in IPDP.

The second contribution is the development of the concept of Information Granularity. RQM does not explicitly cover the complete range of uncertainties as its main focus is on product part and production process uncertainty. In order to have a wider or more complete focus, a top down analysis to select the relevant macro-elements serves as a starting point. Iterative PDP are similar to radical PDP, which are characterised by significant changes that are pre-dominant throughout the PDP [Wheelwright and Clark, 1992]. As such any new method must be flexible enough to remain relevant. The concept of granularity ensures the flexibility of the process to cater for the differences that are inherent in RNI developed in IPDP. It refers to the approach of identifying the macro elements that have high uncertainty, decomposing each of this into more detailed micro-elements so that better uncertainty analysis and assessment can be done. To give an example, the Organizational & Project Management macro element can be broken into External Party Collaboration, External Development Partners, Project Team, Project Resources, Team communication. Each of these micro-elements can then be evaluated in a similar manner and broken into a third level of sub division and so on.

Making the process 'more complete' and 'sub-divided into micro elements' results in a need for more detailed input information. However, it is not possible to obtain or process all of the required information [Simon, 1976], especially in the early phases of the IPDP, to make uncertainty and hence risk assessments. This paradoxical situation is solved by using information that is easily available in the early phases of the IPDP. The concept of resolution is adapted and applied to information so that we have a new dimension called Information Resolution. Information Resolution as used for uncertainty management of RNI in IPDP forms the 3rd contribution of this research. This categorisation is based on classical measurement theory and results in the four types of information resolution level (Nominal information, Ordinal information, Interval information and Ratio information)

[Gigerenzer, et al., 1999] has shown that if minimum (or low-resolution) information is used in a structured environment, it does yield comparable results to traditional complex approaches. Furthermore the results are more applicable or can be better generalized to new data as they are not derived from the results of fitting to specific scenarios and hence are not limited by the constraints of these scenarios.

Different methods for managing risks and to a limited extent uncertainty have been developed over time. RQM [Lu, 2002], FMEA [Lewis, 1996], QFD [PDMA, 2001], Potential-problem analysis [Kepner and Tregoe, 1981] and Risk Diagnosis & Management (RDM) [Halman and Keizer, 1992] require high resolution information. In the early phases of IPDP, decisions need to be made and high resolution information of ratio type and with low uncertainty is preferred but not available. Even if the required information is available, as these methods are very detailed and specific, they can be overwhelming to a project team working under time and resource constraints.

This thesis has shown how low resolution information can be used through the RQM-Lite method to identify uncertainties. After uncertainties are identified, the required information can be gathered so that uncertainty analysis and assessment can be carried out. Through iterations, the information gaps can be reduced resulting in lower uncertainty. Once the required information is obtained to make an estimate of the underlying probability of occurrence, risk analysis and assessments can be carried out using the existing development and quality tools.

The case studies used in the research were based on ongoing projects and conducted in real time in order to reduce history effects that may weaken the research. Whilst this may limit the biases that emerge from the project team members who may taint their comments in light of the project success or failure, it also limits the extent that this research can be prescriptive in the analysis, at least in the academic context. The research findings to a large extent will describe the challenges and activities faced by actual project teams in the field.

### 7.2.2. Implications for Industrial Project Teams

Decisions are required for each and every uncertainty and risk identification, analysis and management. In the context of this research into the reliability of RNI developed in IPDP, these decisions are not only made by the managers but also by the entire project team as they are the subject matter experts. Hence the following discussion on the implications to managers and policy makers will be extended to the project team.

To overcome the effects of negative group dynamics which lead to wishful interpretation rather than objectivity, [Keizer, 2002] proposes the use of individual interviews followed by structured team discussions in the Risk Diagnosing Methodology. This research presents an alternative approach through the use of the concept of information resolution that makes it easier for project teams to make use of low resolution information for more objectivity whilst the negative group effects is reduced by applying the uncertainty estimation process in the 5th step of RQM-Lite method. The default uncertainty indication for an identified element is -1 (more relative uncertainty) which is changed to 0 or 1(equal or less relative uncertainty) only when the required information is available. In this way, even if there is an unwillingness or inability to communicate negative uncertainty or risk, the element or failure mechanism will only be given a positive uncertainty indication when it is supported by the required information.

At the early phases of the IPDP, the RQM-Lite method requires the inputs from the whole project team. In the process, not only will the technological uncertainties be covered, but also the uncertainties related to the other areas such as Marketing, Supply Chain, Organisation, Project Management and cross functional issues.

With these inputs, the uncertainty and hence risk analysis can be carried out. It has been noted by [March and Shapira, 1987] and observed in the case studies of this research that project team members' (human decision makers) ideas about risk differ significantly from the definitions of risk in the theoretical literature and that different individuals will see the same risk situation in quite different ways [Kahneman and Tversky, 1982]. Also it was observed from the case studies in chapter 3, that the project team members were hesitant to make estimates about uncertainty or risk unless they were very certain. These various factors together with the absence of high resolution information in the early phases of the IPDP make the uncertainty and risk management very challenging to the project team. The approach to uncertainty and hence risk management that this research advocates should be understood not as a way of avoiding or limiting uncertainty but as a method to consciously improve understanding so that uncertainty and hence risk decisions can be made objectively and in a structured manner.

The focus of the identified design criteria on the whole is on the process, which should dampen the negative effects that typically arise in control systems that focuses on outcomes [Sitkin and Pablo, 1992]. This supports the observations of [Carter, 1972] that ‘the greater benefits of risk analysis come from the preparation of the model, not from the results’. A focus on the outcome would continually draw attention to, and reward or punish, the successes or failures resulting from a particular decision. In the feedback from the project team during the RQM-Lite implementation, it was also mentioned that the count of the uncertainties should be taken as an indicator to ‘track the progress’ of the project team in terms of uncertainty management and not to be used as a final committed number or target to management.

Lastly, it was noted from the case studies that it took much less effort in terms of time and resources to apply the RQM-Lite method for uncertainty identification. The method was also found to be less overwhelming and prevents the project team from ‘switching-off’. In view of this, the project teams could use it more often and iteratively in light of new information. This formalization of the process also serves as a record and a measure of the project teams’ activities and decisions which can be used to accelerate learning about the product reliability. To paraphrase Lord Kelvin: to understand the risk (or uncertainty) you must be able to measure it.

### 7.2.3. Generalisation

The proposed RQM-Lite method that was used to develop the design criteria uses a top down brainstorming approach for the idea generation and stimulation process that is advantages and can be applied in any industry. The common disadvantage of not covering all areas is overcome by going through the suggested references [Keizer, et al., 2002] list as an additional trigger.

Though the RQM-Lite method was developed in a consumer electronics industry, the flexible yet systematic method is not prescriptive in nature but instead acts as a guiding framework for uncertainty identification. This flexible framework allows it to be used with other technologies beyond the consumer electronics industry. Furthermore, the approach is not limited to technological aspects but also covers organizational, commercial and other areas. On the basis, more research can be done to see if the findings can be generalized to the service industry.

With reference to the five case studies, each in itself contains multiple sub-units that can stand alone in itself, and as such has internal validity. As the cases were selected from different market segments (automotive, audio-video and data), which make the findings more general, the generalisation is limited to RNI developed in IPDP from the consumer electronics industry. More research is required to see if it can be applied to other types of products such as radical innovation which have inherently higher uncertainty due to the macro level discontinuity in both the marketing and technological areas. Theoretically, it should be applicable as the design criteria do not differentiate between the levels of uncertainty in an innovation.

From a product development process perspective, theoretically it should be possible to apply the findings to the different PDPs such as functional, sequential, concurrent and radical PDPs as the design criteria do not differentiate on the whether the processes are performed in batches, linear function, parallel or level of innovation discontinuity. By applying the concept of information resolution proactively, the RQM method can make use of low resolution information that is available in the predictive phase for the uncertainty identification and analysis. This can then be followed up by subsequent applications or iterations during the predictive phase, verification phase and industrialization phase that exists in all of the above PDPs [PDMA, 2004; Clausing, 1994]. As it was not in the scope of this research to apply the findings to these various types of innovations and PDPs, the immediate generalisation based on actual implementations is not possible. The other limitations and future research directions will be addressed next.

## 7.3. Further Research

This research represents efforts to develop the foundation for uncertainty identification and management for RNI developed in IPDP based on a more objective and systematic approach. It has been demonstrated that the prototype RQM-Lite Method works expectedly on the first implementation. However, additional research is needed to empirically test the proposed method, and also apply it on other types of innovations, product development processes and industries as discussed above to increase the robustness and external validity of the findings.

The testing carried out in this research was targeted at validating the design criteria. More research can be done to test the efficacy and efficiency of the RQM-Lite method or any other suitable method that is developed based on the design criteria. This test for the preliminary implementations of the method or tool would need to rely on formal anonymous evaluations among the various project team members that are involved. The questionnaire should contain questions based on a 1-10 Likert Scale. These progressive steps need to be taken to firstly refine the design criteria and improve the RQM-Lite method and secondly to gather sufficient confidence in the process so that firms or companies may be willing to participate in the further research. The full scientific standard of testing should be applied once there are sufficient samples that are randomly taken which represent the population of mature firms in their respective industries that carry out discontinuous innovations.

The RQM-Lite method or any other method developed based on the design criteria should not be used in isolation in the IPDP. Further research should be done to identify how the chosen method can, on an operational level, be integrated with the existing methods such as RQM, FMEA, QFD and other reliability methods in organisations so that the project teams can use these tools more efficiently and thereby effectively.

In the three industrial cases in this research, RQM-Lite method highlights a number of important issues regarding uncertainty identification, which is treated at a high level. Although the research data is notable for its richness and longitudinal nature, it has its limitations. The on-going real time collection of data limits the collection of data regarding perceptions of product success. Such data would permit hypothesis testing rather than exploratory analysis.

In terms of the level of detail, there is no limit to the potential depth of analysis for (uncertainty and hence) risk reduction [Wharton, 1992]. More research can be done to determine the appropriate stopping criteria for the application of information granularity when decomposing the macro-elements into micro-elements. In this way there can be more details yet not too much to overwhelm the project team. This may improve the quality of the results, which may require field results. However due to the complexity of the innovation and the extensive inter dependence of various elements; it may be challenging to isolate a single contributory cause for the field results. Alternatively, mathematical or statistical models may be developed to improve the quality of the results, but these models are also limited by their assumptions and simplifications [Ansell, 1992]. These various options should be seen as complementary rather than as replacements for each other. Though there are limitation with each option, each provide useful insights and improve understanding of the uncertainty and hence risk related to the reliability.

On the aspect of improving the accuracy of uncertainty estimates, reliable field information, when it becomes available, should be used to develop simple heuristics [Gigerenzer, et al., 1999] for risk estimation once the uncertainties have been identified and reduced. This could employ the various approaches to better exploit the limited information such as ignorance-based and one-reason decision making for choice, elimination models for categorization, and satisficing heuristics for sequential search [Gigerenzer, et al., 1999].

However, [March and Shapira, 1987] have found in their literature review that individuals do not trust, do not understand, or simply do not use much precise probability estimates. The decision makers’ insensitivity to probability estimates may reflect such terminology elasticity among writers on risk. Typically, none of the guesses of choice are easy ones. Information is also compromised by conflict of interest between the source of information and the recipient. To a large extent, probability estimates are treated as unreliable and subject to post-decision control, and considerations of trade-offs are framed by attention factors that considerably affect action. It has been recognized that decision making is a complex cognitive task, frequently situation dependent, in which human beings perform in a manner determined by their limited memory, retention and information processing capabilities [Wharton, 1992]. Although this evidence suggest a less optimal risk taking behaviour for decision makers’, it may be necessary to examine the extent to which the decision makers’ belief and behaviour that is observed is an accommodation of human organization and the practical problems of sustaining an appropriate risk taking in an imperfectly comprehended world. The above discussion can be summed up by the elements of the different mode of processing risk, both cognitively and emotionally which include [Shapira, 1995]

- Focusing on a few discrete values (events) in outcome distribution
- Sequentially attending to critical performance targets, of which survival is the most salient
- Dealing with risk in a dynamic process in which estimates are modified, parameters are changed and the problem restructured in an active manner

This behaviour makes the value of standard statistical analyses seem less important. More research can done to better understand this behaviour so that the design criteria and hence RQM-Lite method can be improved to enhance the uncertainty and risk estimation by including the construction of scenarios in situations where probability distributions are non-stationary.  This further research should also cover the managers' attitude towards uncertainty and risk, as some may be more risk averse, risk neutral or risk seeking; and how this affects their use of the RQM-Lite method.

Despite the limitations discussed above, the design criteria developed in this research and the prototype RQM-Lite method used to validate it, when compared to the available alternatives, shows promise especially in the field of uncertainty management of product reliability for RNI in IPDP. The uncertainty and hence risk analysis and assessment may inform the debate, but the resolution of these issues and the uncertainty and risk management at this level will be determined by the decision makers' attitude and considerations.

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## Appendix A: The Reliability & Quality Matrix (RQM)

This appendix will give some general information concerning RQM as developed by [Lu, 2002] in section A.1 and the RQM modified by OC in section A.2. In section A.3 conclusions are drawn.

### A.1. The Reliability Quality Matrix ($1^{st}$ version)

The Reliability & Quality Matrix was developed by [Lu, 2002] as a spreadsheet based supporting tool for the RQM process. The RQM (version 1) process consists of seven steps that need to be executed as defined by [Lu, 2002]:

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

OC made these general steps operational by adjusting some of the terminology. The adapted RQM guidelines at OC are defined as follows:

**Step1: Prioritise Customer Requirements**
Based on discussions with the customer(s), the Customer Requirements are identified. The Requirements are grouped into the three categories: must, linear satisfier and nice to have.
**Step2: Customer Requirement Trade-off Analysis**
Based on the Customer Requirements from step 1, a trade-off analysis is performed.
Step3: Identify the Product Parts / Production Process and Indicate Known / Unknown

First the parts list and the production process flow have to be established. Then this is put into the matrix.

The production processes are listed in the column "Processes" of the matrix. For the process flowchart all assembly steps are mentioned on a separate line. This means that even if multiple parts are assembled on one workstation, they will still appear as separate steps. The list will be in sequence of assembly, starting with the main assembly of the product. If subassemblies are used, the corresponding process flowcharts are inserted just before the assembly of the subassembly. All the parts of the parts list have to be mentioned in this flowchart.

Step4: Identify the Correlation Between Prioritised Customer Requirements and Processes / Parts

For each of the Customer Requirements, its impact on the Processes and Parts will be established. This part is copied from the way of working in a Diversity Analysis.

Step5: Identify Project / Product / Process Risks

The risks for the project, product and processes are identified.

Step6: Predict PPM Level for Both Known / Unknown Processes & Parts

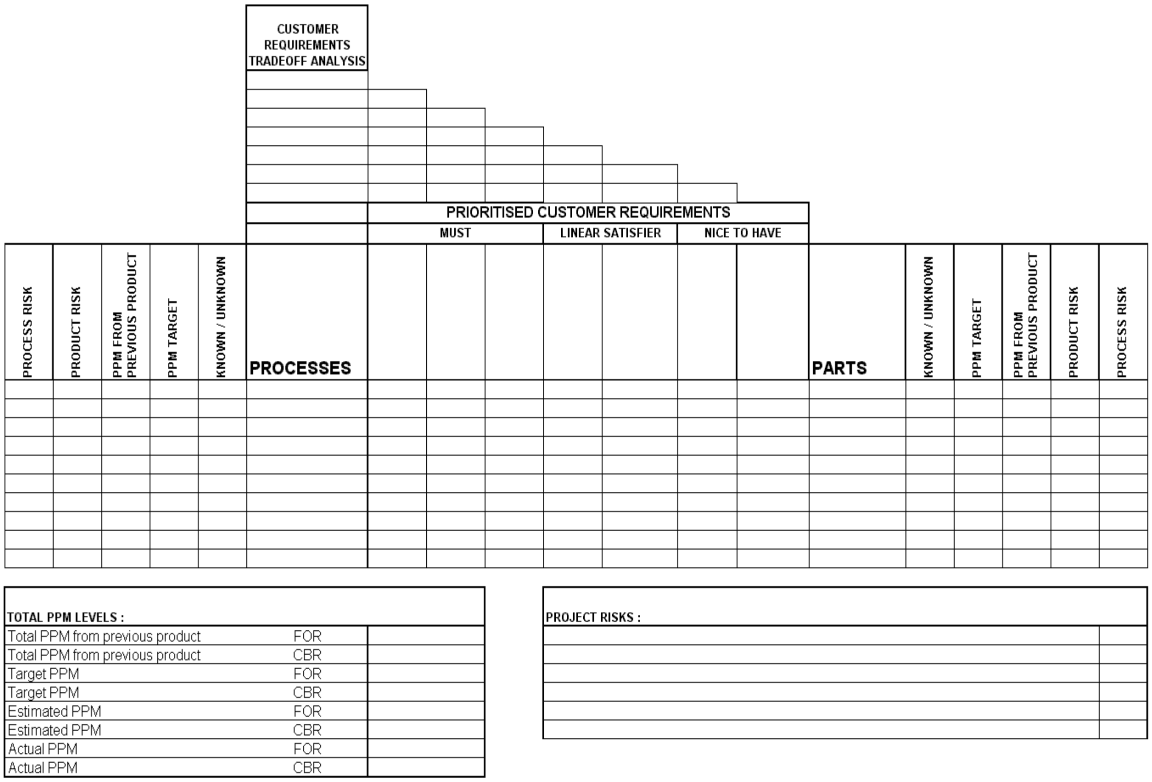
The PPM levels are estimated. For the known processes and parts, the estimates are done by referencing the values from previous products. For the unknown processes and parts the PPM levels are estimated by analysis test results, simulation results or just rough estimates, input from the Cpk of the process, the errors during testing and the yield of repair stations (if any) have to be given in order to statistically calculate the PPM level for these unknown processes. The spreadsheet will indicate the confidence level for the estimation based on the input source. This is done by changing the background colour of the cell to show the accuracy level of the estimation.

Step7: Predict FOR / CBR / FCR

The last step is to predict the quality figures for the total project. This is done by using the inputs from the matrix and inputs from other tools used in the project. The results of the calculations are displayed at the centre bottom of the matrix, for easy reference.

By working through the above structured steps, the uncertainties in the projects related to product parts and process are reduced. The potential risks that are identified are then addressed by the project based on the project needs.

In order to consolidate all the information in a standard way and also to enable better visualisation of the potential risks, the spreadsheet based tool shown in figure A1 was developed and is being used in OC.



CUSTOMER REQUIREMENTS TRADEOFF ANALYSIS

PRIORITISED CUSTOMER REQUIREMENTS

| PROCESS RISK | PRODUCT RISK | PPM FROM PREVIOUS PRODUCT | PPM TARGET | KNOWN / UNKNOWN | PROCESSES | MUST | | | LINEAR SATISFIER | | NICE TO HAVE | | PARTS | KNOWN / UNKNOWN | PPM TARGET | PPM FROM PREVIOUS PRODUCT | PRODUCT RISK | PROCESS RISK |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

| TOTAL PPM LEVELS : | | |
|---|---|---|
| Total PPM from previous product | FOR | |
| Total PPM from previous product | CBR | |
| Target PPM | FOR | |
| Target PPM | CBR | |
| Estimated PPM | FOR | |
| Estimated PPM | CBR | |
| Actual PPM | FOR | |
| Actual PPM | CBR | |

PROJECT RISKS :

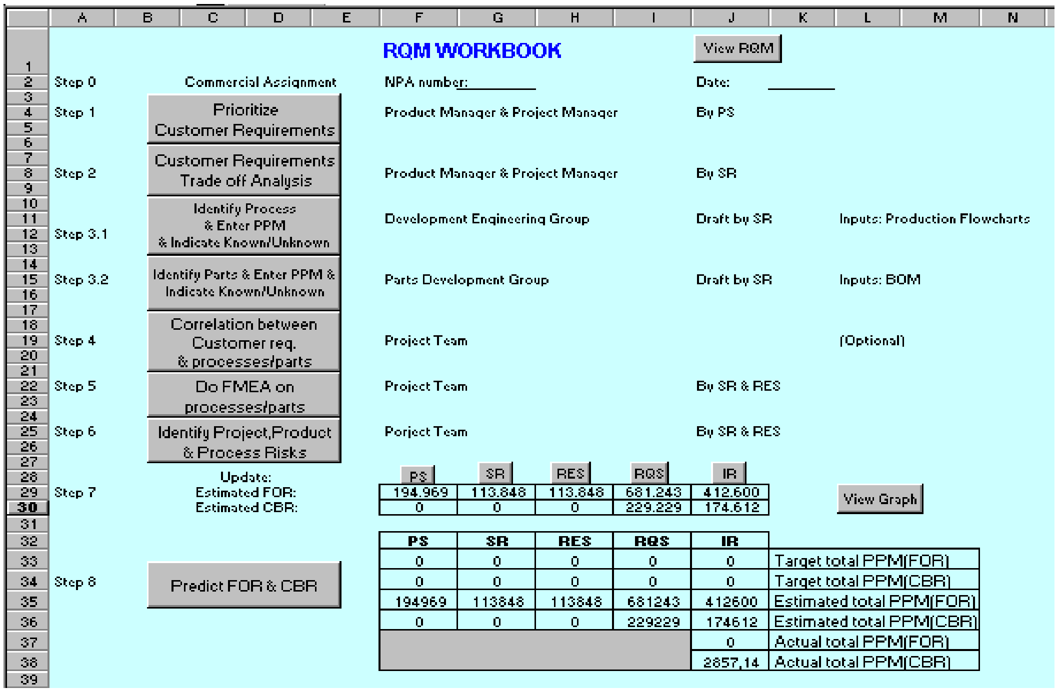
*Figure A1: Structure and Interface of RQM*

However, during the course of application at OC, it was found that the RQM matrix was overwhelming and the data entry process too complicating. It was then improved by adding a user-interface menu with embedded macros to enable easier data entry and act as guide through the seven steps for developers. The modified tool is shown next.

### A.2. The Reliability Quality Matrix (2$^{nd}$ version)

In figure A2, the interface of the improved RQM tool is displayed. It shows the high-level overview screen, which is the start of every subsequent step. Clicking on each step will bring the developer to the respective spreadsheet window that has to be filled-up.

Comparing this interface with the RQM (1st version), it can be seen that improved RQM (2nd version) is less complex and has a better overview due to its clear stepwise approach.



**RQM WORKBOOK**

| | | | | |
|---|---|---|---|---|
| Step 0 | Commercial Assignment | NPA number: | Date: | |
| Step 1 | Prioritize Customer Requirements | Product Manager & Project Manager | By PS | |
| Step 2 | Customer Requirements Trade off Analysis | Product Manager & Project Manager | By SR | |
| Step 3.1 | Identify Process & Enter PPM & Indicate Known/Unknown | Development Engineering Group | Draft by SR | Inputs: Production Flowcharts |
| Step 3.2 | Identify Parts & Enter PPM & Indicate Known/Unknown | Parts Development Group | Draft by SR | Inputs: BOM |
| Step 4 | Correlation between Customer req. & processes/parts | Project Team | | (Optional) |
| Step 5 | Do FMEA on processes/parts | Project Team | By SR & RES | |
| Step 6 | Identify Project,Product & Process Risks | Porject Team | By SR & RES | |

Step 7

| Update: | PS | SR | RES | RQS | IR |
|---|---|---|---|---|---|
| Estimated FOR: | 194.969 | 113.848 | 113.848 | 681.243 | 412.600 |
| Estimated CBR: | 0 | 0 | 0 | 229.229 | 174.612 |

Step 8 Predict FOR & CBR

| PS | SR | RES | RQS | IR | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | Target total PPM(FOR) |
| 0 | 0 | 0 | 0 | 0 | Target total PPM(CBR) |
| 194969 | 113848 | 113848 | 681243 | 412600 | Estimated total PPM(FOR) |
| 0 | 0 | 0 | 229229 | 174612 | Estimated total PPM(CBR) |
| | | | | 0 | Actual total PPM(FOR) |
| | | | | 2857,14 | Actual total PPM(CBR) |

*Figure A2: RQM (2nd Version) High Level Overview Interface*

The improved RQM (2nd version) is conceptually the same as the RQM (1st version). Some of the steps were defined more explicitly and these additional descriptions are listed below.

| RQM (1st version) | RQM (2nd version) |
|---|---|
| Step1: Prioritise Customer Requirements | No new additions |
| Step2: Customer Requirement Trade-off Analysis | No new additions |
| Step3.1: Identify Process & Enter PPM & Indicate Known / Unknown | No new additions |
| Step3.2: Identify Parts & Enter PPM & Indicate Known / Unknown | No new additions |

| | |
|---|---|
| Step4: Identify the Correlation Between Prioritised Customer Requirements and Processes / Parts | No new additions |
| Step5: Identify Project / Product / Process Risks | The risks for the project, product and processes are identified.<br>The project team uses the FMEA sessions to identify and solve the risks. The results of these FMEA sessions are used to fill in the RQM and it provides an overview for FMEA sessions that ensures important issues are not left out. |
| Step6: Predict PPM Level for Both Known / Unknown Processes & Parts | The project team identifies the estimated PPM of each process and part and fills into the improved RQM at PS, SR, RES, RQS and IR. Then the total estimated FOR and CBR can be summed up for PS, SR, RES, RQS and IR. A graph is provided to show the trend of FOR and CBR estimates over the PDP. |
| Step7: Predict FOR / CBR | No new additions |

The design of the improved RQM (2nd version) spreadsheet was more process orientated compared to the RQM (1st version). The new design also enabled all the iterations to be filled up in one file. In this research, the improved RQM (2nd version) was the spreadsheet tool that was used in all the RQM process. As such, whenever RQM is referred, it implies the use of the improved RQM (2nd version) spreadsheet tool.

## A.3. Conclusions

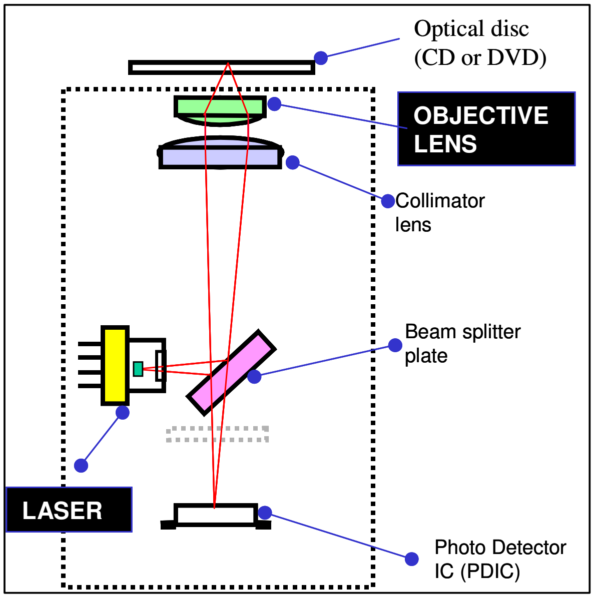
This appendix explained the RQM (1st version) guidelines and the adapted guidelines as defined by OC. The adaptation was done more for practical usage purposes and did not deviate from the intended RQM design framework.

## Appendix B: Exploration Into Reliability Focus In The Field

This appendix will provide a simplified technical explanation of the product under research, that is the Optical Pick Up (OPU) in section B1 followed by a detailed background and findings into the industrial project at OC called RS2 in section B2. The conclusions will then be covered in section B3.

### B.1. The Optical Pick Up (OPU)

The Optical Pick Up (OPU) is a complex opto-electrical module that converts variations in the reflection from an optical disc into an electrical signal.



In a conventional gramophone record, the information is stored in marks or indentations that form a spiral and a mechanical stylus, which comes into the contact with the disc, reads out the information. In the optical disc, the marks on the tracks are small areas showing optical contrast with respect to the surrounding mirror surface. This causes the reflection to change along the track according to the marks or depressions. The optical pickup unit does not come into physical contact with the optical disc but focuses a laser beam to a small spot of light on the track and sends the light reflected off the disc to a photo detector. The photo signal thus varies in time according to the marks along the track of the rotating optical disc.

### B.2. The RS2 Project

The RS2 project was initiated to design in a new type of laser part. As such there was a relatively small degree of innovation and was defined as a derivative project. The main difference between the RS2 and its predecessor was the replacement of the Laser Diode Grating Unit (LDGU) by a Resin Stem. In other words, it is a change from a laser sub assembly unit to a discrete laser in the OPU. This was done for quality purposes, among other things.

Data analysis showed there exist a difference between using an uncertainty including (RQM) and an uncertainty excluding approach (FMEA) for the derivative RS2 case.

Excluding uncertainty obviously leads to the ignorance of a large part of the risks in the predictive phase of the PDP: Only 5 certain failure mechanisms were identified. Many of the potential failure mechanisms were not identified and some of these failure mechanisms showed up as surprises in the evaluation (RQS) phase when reliability verification tests were executed. These surprises could have been prevented by including and managing uncertainty in the predictive phase.

### B.3. Conclusion

This analysis of a case study extracted from the company archives showed that besides risk management, the uncertainty management is also a very important metric that needs to be focused upon and included in the proactive reliability management process.

## Appendix C: Evaluating RQM in The Field

The simplified technical explanation of the product under research, that is the Optical Pick Up (OPU) is explained in appendix B1. In this appendix, an evaluation of the RQM as it is used in industry is carried out by using three case studies. In section C1 and C2, two RNI OPU projects, namely OPU16 and OPU46 are analysed. The derivative OPU42 project is analysed in the third case study in section C3 with overall conclusions drawn in section C4.

### C.1. RNI OPU16 Project (Case study 1)

#### C.1.1. Introduction

The OPU16 is a low cost DVD-Video optical pickup unit using the key component from an internal supplier, Actuator 61 and other discrete components. It is intended to be a “generic" DVD OPU and target to be used in the next generation of DVD Video products. The deliverable for this project was a significant reduction in Bill of Material (BOM) costs and along with this a much simplified manufacturing process and assembly equipment.

In section C.1.2 the RQM data from the OPU16 case is given and a classification in effective and ineffective uncertainty management is made. In section C.1.3 the analysis (type 1 and 2 inaccuracy ratios) is done with conclusions drawn in section C.1.4.

#### C.1.2. Observations

The OPU16 data is depicted in table C1. The values in the column PS give the risk estimates made by the project team for each part and process at the PS milestone in the predictive phase. Similarly the values in the RQS column show the risk estimates made at the RQS milestone during the verification phase.

The risk estimates made at the RQS milestones is analysed and categorised as

Risk that was effectively estimated
Risk that was ineffectively estimated and is of Type 1 nature
Risk that was ineffectively estimated and is of Type 2 nature

Ineffective type 1 uncertainty is due to new failure mechanisms that contribute risk as a result of a lack of information. Ineffective type 2 uncertainty is an increased risk with a known failure mechanism but inaccurately quantified due to insufficient information. For practical reasons, only changes which are significant are considered. This will prevent the research being deviated by influences from “noise factors” such as measurement errors, documentation errors or human errors.

For some of the parts and processes, comments have been given explaining the classification of ineffective type 1 or 2 or effectively managed uncertainty. The newly identified failure mechanisms are depicted in yellow. All other failure mechanisms show either similar or decreased PPM values indicating effective uncertainty management, while the similar or decreased PPM indicates the risk reduction measures taken by the project team.

| **OPU16** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **PROCESSES** | **PARTS** | **PS** | **RQS** | **Ineffective** | | **Effective** | **Comments** |
| | | | | **Type 1** | **Type 2** | | |
| Insert beam splitter, hologram, grating and spring clip | | 996 | 300 | | | 300 | |
| **Squareness measurement** | | | **100** | 100 | | | Not identified in PS |
| | BSP | 2062 | 300 | | | 300 | |
| | HOE | 1 | 351 | | 350 | | |
| | **HOE spring** | | **2282** | 2282 | | | Part was not identified in PS phase and thus type 1 |
| | BSP Spring | 60 | 500 | | 440 | | |
| | OPU Housing | 1 | 29427 | | 29426 | | Identified but wrongly estimated/quantified thus type 2 |
| Glue beam splitter | | 587 | | | | | |
| New failure mechanism | | | 6.318 | 6318 | | | The high RQS value was caused |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | by efficiency of the technical support staff. As this is new failure mechanism is thus type 1 |
| Insert collimator into optical housing | | 259 | 60 | | | 60 | |
| | Collimator | 3301 | 120 | | | 120 | |
| Glue collimator into optical housing | | 587 | 356 | | | 356 | |
| Cut laser leads & insert laser into optical housing | | 1160 | | | | | |
| New failure mechanism | | | 3.257 | 3257 | | | Socio, training, communication is new failure mechanism thus type 1 |
| | Laser | 4864 | 14196 | | 9332 | | Identified but wrongly estimated/quantified thus type 2 |
| Beam measurement ( 25 % ) – provisional | | 314 | | | | | |
| New failure mechanism | | | 3.514 | 3514 | | | Production equipment is New failure mechanism thus type 1. |
| Mount actuator and spring ; manual screw actuator | | 259 | 259 | | | 259 | |
| | Actuator (with objective lens) | 3328 | 3978 | | 650 | | |
| | Actuator Spring | 53 | 120 | | 67 | | |
| | M1.4x4 Screws | 100 | 100 | | | 100 | |
| Mount flex | | 259 | 259 | | | 259 | |
| | Flex Assy | 6810 | 6810 | | | 6810 | |
| **Mount 3rd bearing Spring** | | | **95** | 95 | | | New failure mechanism (not identified in PS) thus type 1 |
| | **3rd Bearing Spring** | | **80** | 80 | | | New failure mechanism (not identified in PS) thus type 1 |
| | **M2x7 Screws** | | **390** | 390 | | | New failure mechanism (not identified in PS) thus type 1 |
| Solder flex to LD and actuator | | 655 | 545 | | | 545 | |
| | **Laser modulator** | | 3276 | 3276 | | | New failure mechanism (not identified in PS) thus type 1 |
| Potmeter Pre-adjustment | | 259 | | | | | |
| New failure mechanism | | | 1.287 | 1287 | | | The high RQS value was caused by efficiency of the technical support staff. As this is new failure mechanism is thus type 1 |
| Actuator Pre-adjustment | | 600 | 400 | | | 400 | |
| DVD ( PDIC ) adjustment [ adj. time = 50 s ] | | 943 | 32.323 | | 31380 | | Identified but wrongly estimated /quantified thus type 2* |
| **ab + Gluing process** | | | **29.544** | 29544 | | | New failure mechanism (not identified in PS) thus type 1 |
| | PDIC-6 segment | 1 | 430 | | 429 | | |
| | M2x5 Screws | 100 | 1 | | | 1 | |
| | M2×7 screws | | 390 | | 390 | | |
| CD ( Hologram & Grating ) adjustment [ adj. time = 35 s ] | | 4096 | 14.606 | | 10510 | | Identified but wrongly estimated/quantified thus type 2 |
| **+ gluing process** | | | **7.878** | 7878 | | | New failure mechanism (not identified in PS) thus type 1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| End Control ( Test time = 20 s ) | | 1 | 🟥 | | | | | |
| New failure mechanism | | | 3.040 | | 3040 | | | Production equipment is new failure mechanism |
| Sub-Assembly (flex) | | 1 | 560 | | | 559 | | |
| Paste label on flex & insert metal plate | | 1 | 210 | | | 209 | | |
| | Label | 19 | 95 | | | 76 | | |
| | EMC Shield | | 155 | | | 155 | | |
| Solder photodiode to flex assy | | 423 | 🟥 | | | | | |
| New failure mechanism | | | 6.552 | | 6552 | | | Efficiency of technical support staff is new failure mechanism thus type 1 |
| Laser modulator assembly | | 191 | | | | | | |
| New failure mechanism | | | 660 | | 660 | | | Efficiency of technical support staff is new failure mechanism thus type 1 |
| | Discrete laser Modulator | 1 | 1 | | | | 1 | |
| | **SUM** | **32.292** | **175.125** | | **68.273** | **83.973** | **9.511** | |
| | | | | | **161.757** | | | |

*Table C1: Uncertainty Classification of OPU16 RQM Data*

The difference between the summed RQS risk of 175.125 and the sum of the ineffectively managed type 1, 2 and effectively managed uncertainties is due to the original risk predictions for the failure mechanisms that are identified as ineffectively managed type 2 uncertainty elements: $\sum_{E\in A,B\wedge y_E>\hat{x}_E}(x_E)$.

C.1.3. Analysis

The relevant elements have been calculated here.

$$\sum_{E\notin A,E\in B} y_E = 68.273$$

$$\sum_{E\in A,B\wedge y_E>\hat{x}_E}(y_E-\hat{x}_E) = 83.973$$

$$\sum_{E\in A,B}\hat{x}_E = 32.609+13.368 = 45.977$$

From the analysis of the OPU16 data it can be concluded that of the 175.125 PPM risk present in the RQS phase 68.273 was due to ineffectively managed type 1 uncertainty, 83.973 was caused by increased risks due to ineffectively managed type 2 uncertainty. 13.368 PPM was predicted for the known failure mechanisms that contained type 2 uncertainty $\sum_{E\in A,B\wedge y_E>\hat{x}_E}(x_E)$.

9.511 PPM was remaining risk after focused risk reduction had been applied on the known correctly quantified failure mechanisms. The latter showed a summed risk $\sum_{E\in A,B\wedge y_E\le\hat{x}_E}(x_E)$ of 32.609 that had been reduced to 9.511 in the RQS phase. All of these values have been visualised in figure C1.

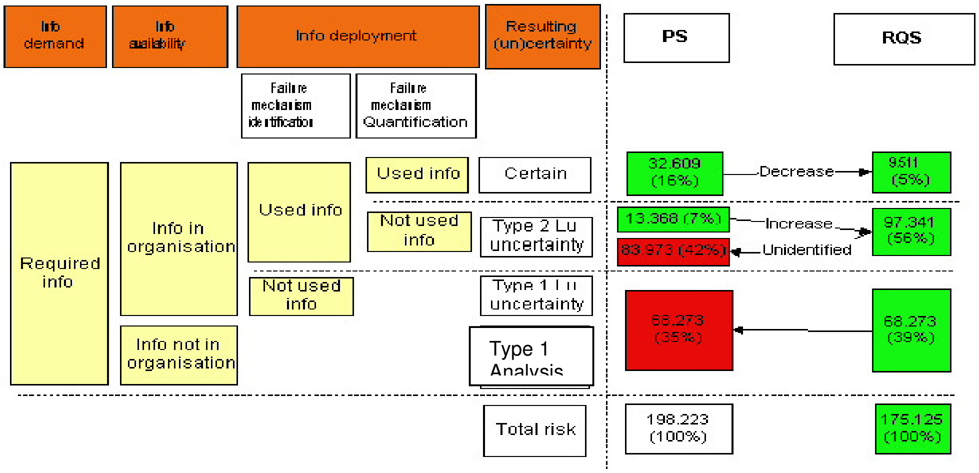


*Figure C1: The Amount of Identified (green) and Unidentified (red) Risk with RQM in the OPU16 Case Study*

The additional risk identified in the RQS phase should have been predicted in the PS phase. This has been visualised in figure C1 where the red squares represent the summed risk not predicted by RQM in the PS phase due to ineffective uncertainty management. The green squares represent the summed predicted risk due to effectively managed uncertainty.

Based on these PPM values the type 1 and 2 inaccuracy ratio is calculated:

Type 1 inaccuracy ratio = 68.273/198.223 = 35%

Type 2 inaccuracy ratio = 83.973/198.223 = 42%

Both of these ratios are much bigger than the ideal value of zero.

### C.1.4. Conclusions

As the type 1 and 2 inaccuracy ratios are 35% and 42% respectively, which is significantly above the ideal value of 0%, it is concluded that RQM is ineffective in managing type 1 and 2 uncertainties in the RNI OPU16 PDP.

## C.2. RNI OPU46 Project (Case study 2)

### C.2.1. Introduction

The OPU46 is “half-height” DVD-OPU targeted for a whole new segment of users who wanted very slim DVD Players. As the expected height reduction is not a few percent reduction from the original OPU16 (Height = 42.5mm) but instead a breakthrough reduction by almost half to 19.8mm in height, the architecture and whole design needs to be changed. As such it was classified as a RNI.

In section C.2.2 the RQM data from the OPU46 case is given and a classification in effective and ineffective (type 1 and 2) uncertainty management per failure mechanism is made. In section C.2.3 the analysis (type 1 and 2 inaccuracy ratios) is executed while conclusions are drawn in section C.2.4.

### C.2.2. Observations

The OPU46 data is depicted in table C2. The values in the column PS give the risk estimates made by the project team for each part and process at the PS milestone in the predictive phase. Similarly the values in the RQS column show the risk estimates made at the RQS milestone during the verification phase.

The risk estimates made at the RQS milestones is analysed and categorised as

Risk that was effectively estimated
Risk that was ineffectively estimated and is of Type 1 nature
Risk that was ineffectively estimated and is of Type 2 nature

Ineffective type 1 uncertainty is due to new failure mechanisms that contribute risk as a result of a lack of information. Ineffective type 2 uncertainty is an increased risk with a known failure mechanism but inaccurately quantified due to insufficient information. For practical reasons, only changes which are significant are considered. This will prevent the research being deviated by influences from “noise factors” such as measurement errors, documentation errors or human errors.

For some of the parts and processes, comments have been given explaining the classification of ineffective type 1 or 2 or effectively managed uncertainty. The newly identified failure mechanisms are depicted in yellow. All other failure mechanisms show either similar or decreased PPM values indicating effective uncertainty management, while the similar or decreased PPM indicates the risk reduction measures taken by the project team.

| **OPU46** | | | | |
|---|---|---|---|---|
| **PROCESSES** | **PARTS** | **SR/ RES** | **RQS** | **Label** |
| Insert BSP and spring | | 120 | | |
| **1)** Assy rejects<br>a) BSP not mounted properly 3/480 = 6,250 PPM b) BSP spring not removed 3/480 = 6,250 PPM Items was not address in FMEA(wrong orientation was been address) | | | **12.500** | Performance of operators/ Sociological |
| | BSP | 210 | | |
| | BSP spring | 500 | | |
| Insert folding mirror & holder, hologram & spring | | 150 | | |
| **2)** Assy rejects FM wrong orientation = 6/480 = 12,500 PPM Items was address in the FMEA - not effective | | | **12.500** | Performance of operators/ Sociological |
| | Folding mirror | 100 | | |
| | HOE | 351 | | |
| | HOE spring | 2.282 | | |
| | OPU housing | 11.771 | 2.083 | |
| Squareness measurement | | 100 | | |
| Glue Beam splitter | | 2.527 | | |
| **3)** BSP glue reject 2/480 = 4,166PPM<br>DVD adj tester Sum C can't focus 71/480 = 147,916 PPM<br>Items 1: Not been address in FMEA(highlight in next project FMEA) Items 2: Not been address in FMEA(highlight in next project FMEA) | | | 152.082 | Production equipment capability |
| Glue folding mirror | | 2.527 | | |
| | Collimator | 120 | | |
| Insert & glue collimator into optical housing | | 416 | | |
| Cut laser leads & insert laser into sink heat and optical housing | | 977 | | |
| **4)** Assy rejects Laser damaged during insertion 2/480 = 4,166 PPM Items not address in FMEA | | | 4.166 | Performance of operators |
| | Laser | 14.196 | | |
| | Heat sink | 4.056 | | |
| Glue laser to heatsink | | 1.440 | | |

| | | | | |
|---|---|---|---|---|
| Glue heatsink to housing | | 1.600 | | |
| Mount & screw cover plate & paste label | | 505 | | |
| | M1.4X4 Screws | 450 | | |
| | Cover plate | 600 | | |
| | Label | 95 | | |
| Beam measurement | | 299 | | |
| Mount actuator spring & actuator | | 220 | | |
| | Actuator(with objective lens) | 3.978 | | |
| | Actuator spring | 120 | | |
| | M1.4X4 Screws | 100 | | |
| Mount & screw flex. Assy | | 259 | | |
| | Flex assy | 6.810 | | |
| Solder flex to laser | | 463 | | |
| aging at70oC for 24hrs | | 293 | | |
| Remove gnd plate, insert FFC and pre-adjust HOE | | 270 | | |
| | FFC | 200 | | |
| Potmeter pre-adjustment | | 708 | | |
| **5)** Potmeter adj reject<br>a) CD Power 41/480 = 85,416 PPM(ESD grounding) b) DVD Power 47/480 = 97,916 PPM(current limiter cct)<br>Items a: Not address in FMEA(only mentioned laser dead due to potmeter overturn Items b: Not address in FMEA | | | 183.332 | Production equipment capability |
| | Potmeter(FFC) | 1.482 | | |
| Actuator pre-adjustment | | 380 | | |
| DVD (PDIC+actuator) adjustment | | 12.929 | | |
| **6)** MP failure a) DVD jitter 7/480 = 14,583PPM b) CD jitter 5/480 = 10,416PPM | | | 24.999 | Production equipment capability |
| 3-D & ab+ gluing process | | 10.340 | | |
| **7)** DVD adj failure<br>a) Vref 6/480 = 12,500PPM b) Others 11 /480 = 22,916PPM<br>MP failure<br>a) DVD BL 6/480=12,500PPM b) Others 16/480=33,333 PPM | | | 81.249 | Production equipment capability |
| CD(hologram) adjustment | | 8.033 | 4.166 | |
| Gluing HOE process and no hold for 24hrs | | 4.727 | | |
| **8)** MP failure<br>CD BL 3/480 = 6,250PPM | | | 6.250 | Production equipment capability |
| DVD potmeter adjustment with EC | | 6.864 | | |
| **9)** MP failure DVD RF 39/480 = 81,250 PPM RF adjustment should always be adjusted in EOL | | | 81.250 | Production equipment capability |
| CD potmeter adjustment with EC | | 936 | | |
| **10)** CD RF 15/480 = 31,250 PPM<br>RF adjustment should always be adjusted in EOL | | | 31.250 | Production equipment capability |
| Solder ESD pad | | 50 | | |
| Sub-assembly(flex) | | 1.496 | | |
| Solder connector board to flex assy | | 560 | | |

| | | | | |
|---|---|---|---|---|
| Solder photodiode to flex assy | | 6.552 | | |
| | PDIC | 430 | | |
| Sub-assembly(actuator) | | 256 | | |
| **11)** DVD adj rejects Lost focus 41/480 = 85,416 PPM Items was not address in FMEA(Dry solder or design problem) | | | 85.416 | Production equipment capability |
| | | | | |
| | **SUM** | **113848** | **681243** | |

*Table C2: Uncertainty Classification of OPU46 RQM Data*

## Ineffective Type 1 uncertainty management

The eleven newly identified failure mechanisms in the RQS phase is shown in table C2. A classification comment is given to explain each label given and the reasoning behind labelling it as an ineffectively managed type 1 uncertainty.

| **Failure mechanism as identified by OC in RQS milestone (OC comment)** | **RQS** | **Classification comment** | **Label** |
|---|---|---|---|
| **1)** Assy rejects<br>a) BSP not mounted properly 3/480 = 6,250 PPM<br>b) BSP spring not removed 3/480 = 6,250 PPM<br>Items was not address in FMEA(wrong orientation was been address) | 12.500 | Bad workmanship is a sub-element of the processes. One did not think about this variable (inexperience) as it is not explicitly mentioned in RQM and therefore it came as a surprise in the RQS phase. | Performance of operators/ Sociological |
| **2)** Assy rejects<br>FM wrong orientation = 6/480 = 12,500 PPM<br>Items was address in the FMEA – not effective | 12.500 | This is a type 1 uncertainty for RQM as it is a new one for RQM. Only because FMEA was applied had one identified this failure mechanism but this was due to 'luck' (experience of user) instead of a structural method (performance of operators var. missing in RQM). | Performance of operators/ Sociological |
| **3)** BSP glue reject 2/480 = 4,166PPM<br>DVD adj tester<br>Sum C can't focus 71/480 = 147,916 PPM<br>Items 1: Not been address in FMEA(highlight in next project FMEA)<br>Items 2: Not been address in FMEA(highlight in next project FMEA) | 152.082 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |
| **4)** Assy rejects<br>Laser damaged during insertion 2/480 = 4,166 PPM<br>Items not address in FMEA | 4.166 | Sub-element of the (assembly) Process element in RQM however, was not discovered in predictive phase | Performance of operators |
| **5)** Potmeter adj reject<br>a) CD Power 41/480 = 85,416 PPM(ESD grounding)<br>b) DVD Power 47/480 = 97,916 PPM(current limiter cct)<br>Items a: Not address in FMEA(only mentioned laser dead due to potmeter overturn<br>Items b: Not address in FMEA | 183.332 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |
| **6)** MP failure<br>a) DVD jitter 7/480 = 14,583PPM<br>b) CD jitter 5/480 = 10,416PPM | 24.999 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |
| **7)** DVD adj failure<br>a) Vref 6/480=12,500PPM b) Others 11/480=22,916PPM<br>MP failure<br>a) DVD BL 6/480=12,500PPM b) Others 16/480=33,333 PPM | 81.249 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |

| | | | |
|---|---|---|---|
| **8)** MP failure<br>CD BL 3/480 = 6,250PPM | 6.250 | Addressed in FMEA due to experienced employees thus it was no new failure mechanism for the organisation. However subsequently one had problems quantifying the risk as the info was apparently not available. As inexperienced employees should be able to identify this failure mechanism as well, it should be included in RQM v2's design. Thus this is due to ineffective Type 1 Analysis uncertainty management causes | Production equipment capability |
| **9)** MP failure DVD RF 39/480 = 81,250 PPM RF adjustment should always be adjusted in EOL | 81.250 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |
| **10)** CD RF 15/480 = 31,250 PPM<br>RF adjustment should always be adjusted in EOL | 31.250 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |
| **11)** DVD adj rejects<br>Lost focus 41/480 = 85,416 PPM<br>Items was not address in FMEA(Dry solder or design problem) | 85.416 | Element that is not included in RQM reasoning as it is not part of the Processes and Part elements. Therefore it came as a surprise. | Production equipment capability |
| **SUM** | **674.994** | | |

*Table C3: Newly Identified Failure Mechanisms due to Ineffectively Managed Type 1 Uncertainty in OPU46*

Table C3 shows that most of the new risk identified in the RQS phase is due to the element ‘production equipment capability’. As this element depends on OC’ equipment manufacturers, minimal information was available but it was not in any form that was usable for the project team to make neither uncertainty estimates nor improvements. The newly identified risk is thus caused by ineffective type 1 uncertainty management.

### C.2.3. Analysis

The relevant elements have been calculated here.

$$\sum_{E\notin A, E\in B} y_E = 674.994$$

$$\sum_{E\in A,B \wedge y_E > \hat{x}_E} (y_E - \hat{x}_E) = 0.0$$

$$\sum_{E\in A,B} \hat{x}_E = 113.848+0.0 = 113.848$$

From the analysis of the OPU46 data it can be concluded that of the 861.243 PPM risk present in the RQS phase 674.994 PPM was due to ineffectively managed type 1 uncertainty. No PPM increase was caused by ineffectively managed type 2 uncertainty. 113.848 PPM was predicted for the known failure mechanisms that contained type 2 uncertainties $\sum_{E\in A,B\wedge y_E>\hat{x}_E}(x_E)$.

Of which only 6.249 PPM was remaining risk after focused risk reduction had been applied on the known correctly quantified failure mechanisms. All of these values have been visualised in figure C2.

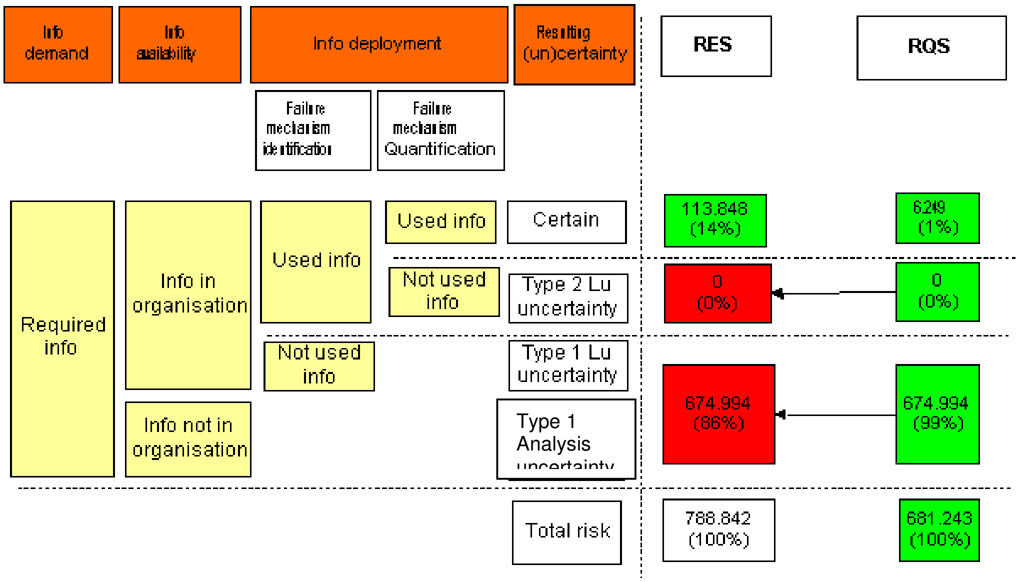


*Figure C2: The Amount of Identified (green) and Unidentified (red) Risk with RQM in the OPU46 Case.Study*

The additional risk identified in the RQS phase should have been predicted in the PS phase. This has been visualised in figure C2 where the red squares represent the summed risk not predicted by RQM in the PS phase due to ineffective uncertainty management. The green squares represent the summed predicted risk due to effectively managed uncertainty.

Based on these PPM values the type 1 and 2 inaccuracy ratio is calculated:

Type 1 inaccuracy ratio = 674.994/788.842 = 86%.

Type 2 inaccuracy ratio = 0%

The type 1 inaccuracy ratio is much bigger than the ideal value of zero.

### C.2.4. Conclusions

The OPU46 case showed two things. Firstly, RQM can effectively manage type 2 uncertainties as the inaccuracy ratio is 0%. However, RQM cannot be used to manage type 1 uncertainties effectively as the type 1 inaccuracy ratio is 86%.

It is shown that most of this ineffective type 1 uncertainty management is due to ineffective Analysis uncertainty.

## C.3. Derivative OPU42 Project (Case study 3)

### C.3.1. Introduction

The OPU42 is also a “half-height” DVD-OPU that is based on the OPU46 platform. The project was initiated to make the minor changes so that it was compatible to a competitor’s OPU and to introduce some cost savings in the Bill of Material (BOM). This would enable the organization to target a larger accessible market share and be used as a second source component for drive makers who had already designed in the competitor’s OPU. As the changes involved minor changes to the form factor of the OPU to make it “drop-in” compatible and to include lower costs components, it was classified as an incremental innovation.

In section C.3.2 the RQM data from the OPU42 case is given and a classification of effective and ineffective (type 1 and 2) uncertainty management per failure mechanism is done. In section C.3.3 the analysis (type 1 and 2 inaccuracy ratios) is executed with conclusions drawn in section C.3.4.

### C.3.2 Observations

Table C3 shows that four new failure mechanisms were identified in the OPU42 case. All of them were due to product equipment problems and are marked yellow in the table. These failure mechanisms were not identified in the predictive (PS milestone) phase as these failure mechanisms are not part of RQM’s failure mechanisms format; in other words, they are not within the scope of product process or part.

These four newly identified failure mechanisms logically were caused by an ineffectively managed type 1 uncertainty. More accurately, they were due to ineffective type 1 Analysis uncertainty as they relate to failures caused by external failure mechanisms that the organisation has no info about.

| **OPU42** | | | | | **Ineffective** | | |
|---|---|---|---|---|---|---|---|
| **PROCESSES** | **PARTS** | **PS** | **RQS** | | **Type 1** | **Type 2** | **Effective** |
| Insert BSP and Spring | | 0 | 0 | | | | 0 |
| | BSP | 9.230 | 90 | | | | 90 |
| | BSP spring | 500 | 150 | | | | 150 |
| | Housing | 31.634 | 9.490 | | | | 9.490 |
| Glue Beam Splitter | | 5.080 | 1.524 | | | | 1.524 |
| Insert and Glue Folding mirror | | 6.360 | 1.666 | | | | 1.666 |
| | Folding Mirror | 200 | 60 | | | | 60 |
| Squareness measurement | | 400 | 120 | | | | 120 |
| Insert Hologram & Spring | | 0 | 0 | | | | 0 |
| | Hologram | 308 | 36 | | | | 36 |
| | Hologram Spring | 462 | 30 | | | | 30 |
| Insert & glue collimator into optical housing | | 2.280 | 684 | | | | 684 |
| | Collimator | 200 | 60 | | | | 60 |
| Mount Heatsink to Housing and Glue Heatsink | | 500 | 150 | | | | 150 |
| Apply Heat compound and Mount cover plate | | 500 | 150 | | | | 150 |
| | Cover plate | 200 | 60 | | | | 60 |
| Paste Label and Beam Measurement | | 6.154 | 3.367 | | | | 3.367 |
| | Label | 0 | 0 | | | | 0 |
| Mount Flex & Washer to Housing | | 0 | 0 | | | | 0 |
| | Washer | 100 | 30 | | | | 30 |
| Mount actuator spring & actuator to Housing | | 0 | 0 | | | | 0 |
| | Actuator(with objective lens) | 155.077 | 15.507 | | | | 15.507 |
| | Actuator Spring | 200 | 60 | | | | 60 |
| | M1.4X4 Screws | 200 | 60 | | | | 60 |
| Solder Flex to Actuator and Solder Flex to laser & Pin | | 200 | 60 | | | | 60 |
| Aging at70oC for 24hrs | | 0 | 0 | | | | 0 |
| Remove gnd plate, insert FFC and pre-adjust HOE | | 200 | 60 | | | | 60 |
| Actuator pre-adjustment | | 0 | 0 | | | | 0 |
| Resistor Search, DVD (PDIC+actuator) Adj and Glue PDIC | | 76.153 | 27.719 | | | | 27.719 |
| DVD Resistor Soldering | | 300 | 90 | | | | 90 |
| | DVD Resistor | 1.846 | 554 | | | | 554 |
| Glue Actuator | | 11.360 | 0 | | | | 0 |
| **Production Equipment capability** | | | **14.705** | | **14.705** | | |
| CD Resistor Search and CD(HOE) Adjustment | | 2.900 | 870 | | | | 870 |
| CD Resistor Soldering | | 300 | 60 | | | | 60 |
| | CD Resistor | 1.846 | 554 | | | | 554 |
| Glue HOE and Onhold for 24 hrs | | 104.923 | 15.522 | | | | 15.522 |
| DVD End Control and CD Control | | 15.380 | 4.614 | | | | 4.614 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Solder ESD pad | | 400 | 120 | | | | 120 |
| Sub-assembly(laser), insert pin to Housing | | 200 | 60 | | | | 60 |
| | Pin | 0 | 0 | | | | 0 |
| Cut Laser leads. Insert and Glue Laser to Heatsink | | 300 | 0 | | | | 0 |
| **Production Equipment capability** | | | **1.683** | | **1.683** | | |
| | Laser | 19.383 | 5.815 | | | | 5.815 |
| | Heatsink | 0 | 0 | | | | 0 |
| Sub-assembly(flex), Solder PDIC to Flex assy | | 0 | 0 | | | | 0 |
| **Production Equipment** | | | **2.534** | | **2.534** | | |
| | Flex | 800 | 240 | | | | 240 |
| | PDIC | 1.000 | 0 | | | | 0 |
| **Production Equipment** | | | **2.534** | | **2.534** | | |
| | | **PS** | **RQS** | | | | |
| | **SUM** | 457.076 | 111.088 | | 21.456 | 0 | 89.632 |
| | | | | | 111.088 | | |

*Table C4: Uncertainty Classification of OPU42 RQM Data*

### C.3.3 Analysis

The four new failure mechanisms added a 21.456 PPM ( $\sum_{E \notin A, E \in B} y_E$ ) to the project risk in the RQS phase that had not been predicted due to Analysis uncertainty in the PS phase. This resulted in a 4% type 1 Analysis inaccuracy ratio.

An overview of the calculations has been given in figure C3.

Based on these PPM values the type 1 and 2 inaccuracy ratio is calculated:

Type 1 inaccuracy ratio = 0%

Type 2 inaccuracy ratio = 21.456/478.532 = 4% ~ 0%

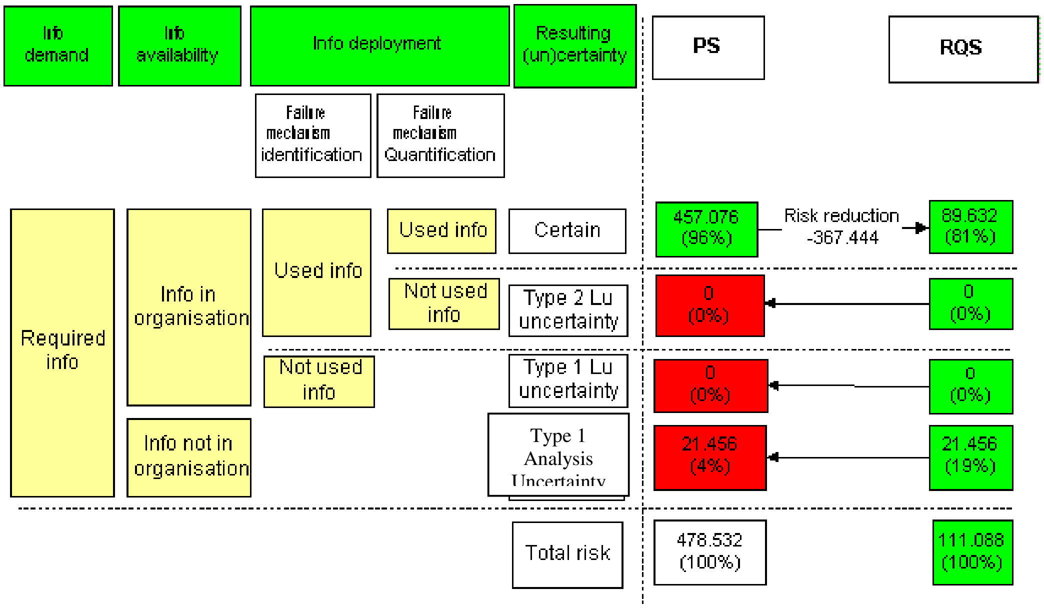


*Figure C3: The Amount of Identified (green) and Unidentified (red) Risk with RQM in the OPU42 Case Study.*

The analysis of the derivative OPU42 was aimed at verifying that RQM is capable of uncertainty management at a time when the improved RQM ($2^{nd}$ version) was applied to IPDP. As can be seen in figure C3 no ineffectively managed Lu uncertainty has been observed. This resulted in a type 1 and type 2 inaccuracy ratios of 0% when the Analysis uncertainty of 4% was excluded.

### C.3.4 Conclusions

The analysis of the OPU42 case revealed that RQM, just as in [Lu, 2002], can effectively manage uncertainties for incremental innovations developed in a derivative PDPs.

## C4 Overall Conclusion

The three industrial case studies confirm that the RQM method is applied in the industry with some adaptation to make it easier for the developers to enter the information into the spreadsheet RQM Tool. The project OPU42 shows that RQM can effectively manage uncertainty and thereby reduce risks as intended. The same is not true when the RQM method is applied to RNI developed in IPDP as the type 1 and 2 inaccuracy ratios are not ideally zero for all the RNI case studies. Hence the RQM method is unable to manage uncertainty for RNI developed in IPDP

## Appendix D: Validation of RQM-Lite Design in The Field

The simplified technical explanation of the product under research, which is the Optical Pick Up (OPU) is explained in appendix B1. In this appendix, a validation of the RQM-Lite prototype design in the industry is carried out by using three case studies. The application of RQM-Lite on three RNI OPU projects, namely OPU66, OPU86 and OPU86 is presented in sections D1 to D3. Overall conclusions are drawn in section D4.

### D.1. RNI OPU66 Project (Case study 4)

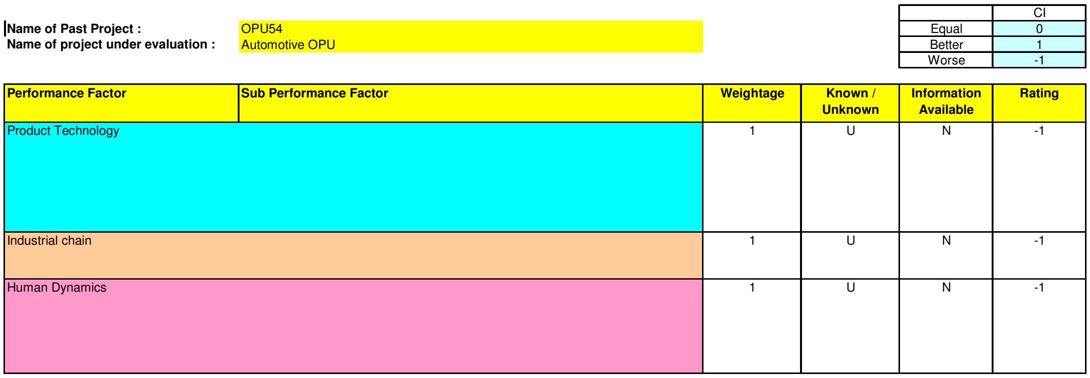
#### D.1.1. Introduction

OPU66 was a project that was initiated in the company to enter the automotive OPU segment. The specifications required for the automotive OPU are much more demanding than that for audio-video OPU [Internal Philips]. The automotive OPU is expected to withstand a wider range of operational and non-operational climates as well as more severe transportation requirements when compared to a DVD Player that is used in a stable home user environment. In order to meet these severe requirements, the OPU has to be redesigned to withstand the higher transportation and climatic shocks. As such it is considered as a IPDP.

In section D.1.2 the RQM-Lite data from the OPU66 case is given. Section D.1.3 covers the analysis of the data and conclusions are drawn in section D.1.4.

#### D.1.2 Observations

The OPU66 RQM-Lite data is shown in figure D1 below. It was used before the concept study milestone in the predictive phase of the PDP. OPU66 was referenced against the OPU54 product. Three uncertainty elements, namely Product Technology, Manufacturing Technology and Organization & Project Management were identified as the high level categories to ensure suitable coverage. None of these elements were broken down into uncertainty sub-elements as the project was at the very preliminary phase. As all the uncertainty elements had changes compared to OPU54 and there was no information available to indicate that anyone was less uncertain than the other, the weightage of 1 was given to each one of it. In the context of the new specification requirements, each of these elements were uncertain and there was no information available which resulted in a CI rating of –1 for each of them. As such the risk level was also unknown for each of these elements.



**Name of Past Project :** OPU54
**Name of project under evaluation :** Automotive OPU

| | CI |
|---|---|
| Equal | 0 |
| Better | 1 |
| Worse | -1 |

| **Performance Factor** | **Sub Performance Factor** | **Weightage** | **Known / Unknown** | **Information Available** | **Rating** |
|---|---|---|---|---|---|
| Product Technology | | 1 | U | N | -1 |
| Industrial chain | | 1 | U | N | -1 |
| Human Dynamics | | 1 | U | N | -1 |

*Figure D1: OPU66 RQM-Lite Data*

Summing up all the data, the following is obtained:

Count of Known elements : 0

Count of Unknown elements : 3

Count of elements with information available : 0

Count of elements with no information available : 3

Count of elements with higher uncertainty ratings (- 1) : 3

Count of elements with equal uncertainty ratings ( 0 ) : 0

Count of elements with lower uncertainty ratings (+ 1) : 0

As this project did not have a project manager assigned to it, the research activities were all done with the product manager. The feedback on the RQM-Lite from the product manager who has used RQM in the past is that this approach is more comprehensive as it is top-down. There is no dependency on the “openness” of the project team members as the default level is “risky” unless proven otherwise with information. The approach is less overwhelming when compared to the detailed milestone checklist and RQM.

When compared to the Project Maturity Grid which is used internally in Philips to assess all other project risk, the RQM-Lite is more systematic and more comprehensive as it guides the developer to establish the risks of the projects. He found it as a “useful background framework” to highlight risks and facilitate decision making.

### D.1.3. Analysis

The RQM-Lite was done at a very early phase of the PDP and did not require detailed information as inputs. The results show that all the major elements have a risk though the quantum is unknown. In this case, it is clear which areas the project team needs to apply attention in order to determine the risk level and quantify it. By applying this approach, the uncertainty has been reduced, as there are no areas that are ‘assumed’ to be of low risk and thereby become uncertainties at the later phases of the PDP.

### D.1.4. Interview & Evaluation

| |
|---|
| Evaluation Question<br>How does this method compare with existing methods for uncertainty management of product reliability ?<br>Any other feedback ? |
| Response<br>1. This only serves as a background framework to highlight risks (uncertainty), it s not used as project maturity indicator<br>2. This is more systematic than project maturity grid to provide a more comprehensive risk (uncertainty) estimate<br>3. Regardless of team openness, this is more comprehensive and locks all potential risks (uncertainty) |
| Other Feedback<br>1. If you have a detailed checklist, people get overwhelmed with the number and switch off, also not all checklist are relevant for all types of projects |

### D.1.5. Conclusions

The OPU66 case has shown that RQM-Lite can be used proactively and with less high resolution information. It surfaced the areas where there are potential risks and thereby has reduced the uncertainty in the project.

## D.2. RNI OPU86 Project (Case study 5)

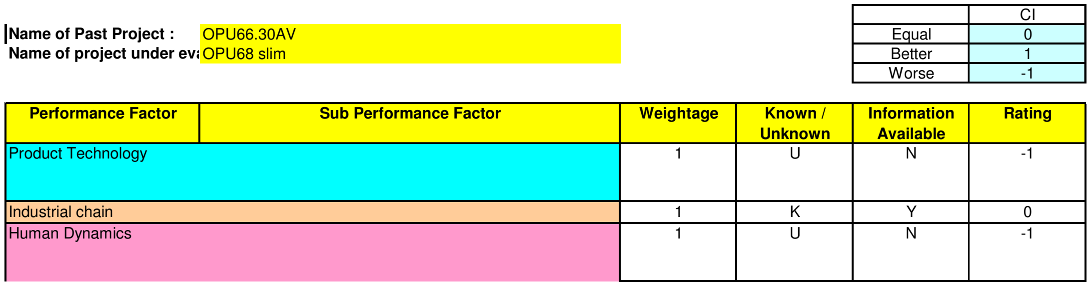
### D.2.1. Introduction

OPU86 or Notebook OPU was a project that was initiated in the company to enter the notebook market segment. It required the OPU to be ultra slim in form factor and as such required a new product architecture and design. The key components to be used had to be newly designed or sourced as the key components used in the OPU54 or other OPU projects could not be reused. As such it is considered as a RNI.

In section D.2.2 the RQM-Lite data from the OPU86 case is given. Section D.2.3 covers the analysis of the data and conclusions are drawn in section D.2.4.

### D.2.2 Observations

The OPU86 RQM-Lite data is shown in figure D2 below. It was at the RES milestone in the predictive phase of the PDP.  OPU86 was referenced against the OPU63 product in the company as that was considered the closest reference. Three uncertainty elements, namely Product Technology, Manufacturing Technology and Organization & Project Management were identified as the high level categories to ensure suitable coverage. As all the uncertainty elements had changes compared to OPU63, the weightage of 1 was given to each one of it.



**Name of Past Project :** OPU66.30AV
**Name of project under ev** OPU68 slim

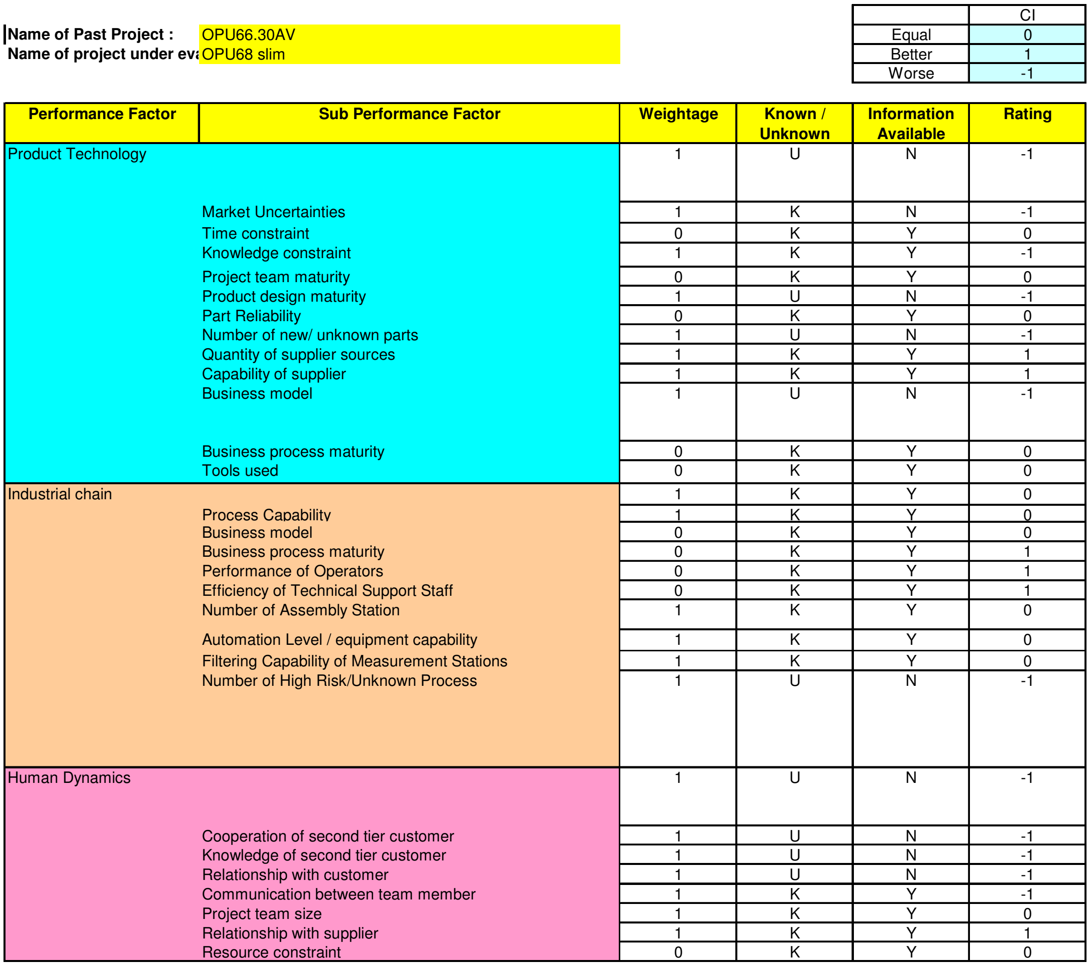
| | CI |
|---|---|
| Equal | 0 |
| Better | 1 |
| Worse | -1 |

| Performance Factor | Sub Performance Factor | Weightage | Known / Unknown | Information Available | Rating |
|---|---|---|---|---|---|
| Product Technology | | 1 | U | N | -1 |
| Industrial chain | | 1 | K | Y | 0 |
| Human Dynamics | | 1 | U | N | -1 |

*Figure D2: OPU86 RQM-Lite Data*

In OPU86, the project manager found it necessary to further sub-divide the macro-elements into more detailed sub-elements, especially when the Manufacturing Technology element was a known element and there was some information already with the project team. By applying the information granularity approach, the micro-elements are identified as shown in figure D3.

By applying the steps for RQM-Lite as explained in section 5.2.2, the CI rating was given to each micro-element. There 22 known elements and 9 unknown elements. One of the elements, ‘market uncertainty’ was known to the organisation and project team as the team knew what the market wanted in terms of a notebook OPU. However the immediate customer in this project still had not made any firm orders or commitment for the OPU that he wanted to design into his notebook. This ‘known element’ was then classified as having not enough information to enable uncertainty estimation. As such, this resulted in 10 of the elements being classified as elements without information. Of the 21 micro-elements with information, only 6 were identified as being less uncertain when compared to the similar element in OPU63. For these 6 elements, the risk levels were quantified. The rest of the elements were either comparable or more uncertain resulting in unknown risk estimates and a CI of 0 or –1.



**Name of Past Project :** OPU66.30AV
**Name of project under eva** OPU68 slim

| | CI |
|---|---|
| Equal | 0 |
| Better | 1 |
| Worse | -1 |

| Performance Factor | Sub Performance Factor | Weightage | Known / Unknown | Information Available | Rating |
|---|---|---|---|---|---|
| Product Technology | | 1 | U | N | -1 |
| | Market Uncertainties | 1 | K | N | -1 |
| | Time constraint | 0 | K | Y | 0 |
| | Knowledge constraint | 1 | K | Y | -1 |
| | Project team maturity | 0 | K | Y | 0 |
| | Product design maturity | 1 | U | N | -1 |
| | Part Reliability | 0 | K | Y | 0 |
| | Number of new/ unknown parts | 1 | U | N | -1 |
| | Quantity of supplier sources | 1 | K | Y | 1 |
| | Capability of supplier | 1 | K | Y | 1 |
| | Business model | 1 | U | N | -1 |
| | Business process maturity | 0 | K | Y | 0 |
| | Tools used | 0 | K | Y | 0 |
| Industrial chain | | 1 | K | Y | 0 |
| | Process Capability | 1 | K | Y | 0 |
| | Business model | 0 | K | Y | 0 |
| | Business process maturity | 0 | K | Y | 1 |
| | Performance of Operators | 0 | K | Y | 1 |
| | Efficiency of Technical Support Staff | 0 | K | Y | 1 |
| | Number of Assembly Station | 1 | K | Y | 0 |
| | Automation Level / equipment capability | 1 | K | Y | 0 |
| | Filtering Capability of Measurement Stations | 1 | K | Y | 0 |
| | Number of High Risk/Unknown Process | 1 | U | N | -1 |
| Human Dynamics | | 1 | U | N | -1 |
| | Cooperation of second tier customer | 1 | U | N | -1 |
| | Knowledge of second tier customer | 1 | U | N | -1 |
| | Relationship with customer | 1 | U | N | -1 |
| | Communication between team member | 1 | K | Y | -1 |
| | Project team size | 1 | K | Y | 0 |
| | Relationship with supplier | 1 | K | Y | 1 |
| | Resource constraint | 0 | K | Y | 0 |

*Figure D3: OPU86 RQM-Lite Data with Micro-Elements*

Summing up all the data, the following is obtained:

Count of Known elements : 22

Count of Unknown elements : 9

Count of elements with information available : 21

Count of elements with no information available : 10

Count of elements with higher uncertainty ratings (- 1) : 12

Count of elements with equal uncertainty ratings ( 0 ) : 13

Count of elements with lower uncertainty ratings (+ 1) : 6

The feedback on the RQM-Lite from the project manager is that it is useful to highlight uncertainties and high level project risks.

### D.2.3. Analysis

The RQM-Lite was done at an early phase of the PDP and did not require detailed information as inputs. The results show that none of the macro elements has less uncertainty when compared to the OPU63. However as one the macro-element, ‘Manufacturing Technology’ was known, the project team then applied information granularity to get a more detailed insight into the risks. As it was easy enough to do, the project manager did the same for the other two macro elements as well, resulting in the uncertainty estimate being done on 31 elements. This helped to identify to a more detailed level where the uncertainties are.

If the project team had not applied RQM-Lite and only used RQM, they would not have detected the uncertainties related to

Time constraint
Knowledge constraint
Project team maturity
Product design maturity
Quantity of supplier sources
Capability of supplier
Business model
Business process maturity
Quality Tools used

Performance of Operators
Efficiency of Technical Support Staff
Automation Level / equipment capability
Cooperation of second tier customer
Knowledge of second tier customer
Relationship with customer
Communication between team member
Project team size
Relationship with supplier
Resource constraint

In this case, the project team needs to apply attention in the areas or elements that have a CI rating of 0 or –1 in order to determine the risk level and quantify it. By applying this approach, the uncertainty has been reduced in these areas along with the conventional areas of RQM.

### D.2.4. Interview & Evaluation

| |
|---|
| Evaluation Question<br>How does this method compare with existing methods for uncertainty management of product reliability ?<br>Any other feedback ? |
| Response<br>1. The number (count of uncertainty elements) is dangerous as it is taken by top mgmt as final committed number<br>2. It is frequently forgotten under what assumptions and information set it was based on<br>3. Useful to identify quickly the weak areas<br>4. Useful to track own progress (in terms of count of uncertainty elements)<br>5. Useful to highlight uncertainties and high level project risks |
| Other Feedback<br>1. Should be used as one of the checklist to support project selection model, to select among projects on which to go<br>2. Not to be used to change existing excution work as current execution will go on anyhow |

### D.2.5. Conclusions

The OPU86 case has shown that RQM-Lite can be used proactively and with less high resolution information. The macro-elements were sub-divided into micro-elements to enable more detailed uncertainty assessment. It surfaced the areas where there are potential risks and thereby has reduced the uncertainty in the project.

## D.3. RNI OPU76 Project (Case study 6)

### D.3.1. Introduction

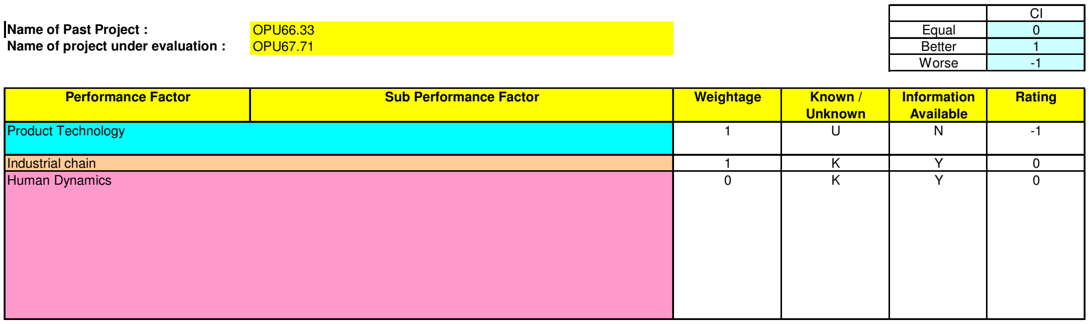
The OPU76 is a rewritable OPU unlike the OPU51 and OPU54 which are read-only OPUs. The project team was given the assignment to have a smaller OPU (height < 17.3mm), with lower cost and design in the dual wavelength lasers instead of the two single discrete lasers which are the common lasers used in the other rewritable OPUs designed in the organisation. This meant it had to have a new design, a drastic component reduction and changes to the assembly process. To realise this, the product architecture had to be redesigned completely and assembly process changed. As such this is considered as a RNI.

In section D.3.2 the RQM-Lite data from the OPU76 case is given. Section D.3.3 covers the analysis of the data and conclusions are drawn in section D.3.4.

### D.3.2 Observations

The OPU76 RQM-Lite data is shown in figure D4 below. It was used before the RES milestone in the predictive phase of the PDP. OPU76 was referenced against the OPU33 rewritable OPU. Three uncertainty elements, namely Product Technology, Manufacturing Technology and Organization & Project Management were identified as the high level categories to ensure suitable coverage. None of these elements were broken down into uncertainty sub-elements as the project team did not feel the necessity. The human dynamic macro-element was given a weightage of 0 as it was the only macro-element which had no changes when compared to the previous product OPU33. This meant it was a known element and there was information available. This information showed that the uncertainty in the area of Organization & Project Management is comparable to the past product and the CI was rated as 0.

For the macro-element of product technology and Manufacturing Technology, there were changes when compared to the past product and as such the weightage was given a 1. As there was no information on the product technology and it was an unknown element, the CI rating was given a –1. However in the case of the Manufacturing Technology, it was a known macro-element and there was information, which was used to arrive at the CI rating of 0. As such the risk level was unknown for the product technology element only.



**Name of Past Project :** OPU66.33
**Name of project under evaluation :** OPU67.71

| | CI |
|---|---|
| Equal | 0 |
| Better | 1 |
| Worse | -1 |

| Performance Factor | Sub Performance Factor | Weightage | Known / Unknown | Information Available | Rating |
|---|---|---|---|---|---|
| Product Technology | | 1 | U | N | -1 |
| Industrial chain | | 1 | K | Y | 0 |
| Human Dynamics | | 0 | K | Y | 0 |

*Figure D4: OPU76 RQM-Lite Data*

Summing up all the data, the following is obtained:

Count of Known elements : 2

Count of Unknown elements : 1

Count of elements with information available : 2

Count of elements with no information available : 1

Count of elements with higher uncertainty ratings (- 1) : 1

Count of elements with equal uncertainty ratings ( 0 ) : 2

Count of elements with lower uncertainty ratings (+ 1) : 0

The feedback on the RQM-Lite from the project manager who has used RQM in the past is that this approach if used objectively is useful. The count of the CI ratings should not be used as targets for the project team to achieve but serve as an indication of the risk areas. This will prevent the ratings from being manipulated and allow it to be used as per the RQM-Lite objective.

### D.3.3. Analysis

The RQM-Lite was done at a very early phase of the PDP and did not require detailed information as inputs. The results showed that only one major element, product technology has an unknown risk while the other two elements have a known risk that the team can compute. In this case, it is clear in which areas the project team needs to apply attention in order to determine the risk level and quantify it.

By applying this approach, the uncertainty has been reduced in all three macro-elements. It has been confirmed with available information that the macro-element of Manufacturing Technology and Organization & Project Management has no uncertainty.

### D.3.4. Interview & Evaluation

| |
|---|
| <u>Evaluation Question</u><br>How does this method compare with existing methods for uncertainty management of product reliability ?<br>Any other feedback ? |
| <u>Response</u><br>1. Used objectively, it is useful<br>2. Use the index as an indicator and with some maturity, not as an absolute<br>3. There should not be targets for each project, then it would easily be manipulated |
| <u>Other Feedback</u> |

### D.3.5. Conclusions

The OPU76 case has shown that RQM-Lite can be used proactively and with less high resolution information. It surfaced the areas where there are potential risks and thereby has reduced the uncertainty in the project.

## D4 Overall Conclusion

In this appendix the RQM-Lite method was applied on three RNI OPU projects in the industry to demonstrate the validity of the prototype design. In all three cases it was found that the method was able to guide the developers to identify the uncertainties, thereby converting it to potential risks which then can be addressed by the project team. Hence this shows that the prototype RQM-Lite design is able to manage uncertainties in IPDP.

## Appendix E: The Generic Proactive Reliability Management (PRM) Process

In this appendix the different steps of the generic proactive reliability management (PRM) process as explained in detail and depicted in figure 2.4 is elaborated in section E1. Conclusions are drawn upon in section E2.

### Review of currently available reliability methods

Proactive reliability management approach requires uncertainty and risk predictions to be made early in the PDP. Logically risk predictions can only be made when there is enough information in the product development [Berden et. Al, 2000] that is, when uncertainty is low. However, as RNIs are in fact characterised by a high degree of Analysis (Type I) uncertainty, uncertainty awareness management must be done first (figure 2.3) before risk management.

A selection of currently available reliability methods will be reviewed based on the following criteria that have been derived from the discussions in the preceding sections.

**Criterion 1: Proactiveness**

+ used during the predictive phase of the PDP
- not used during the predictive phase of the PDP

**Criterion 2: Risk Awareness**

+ focus on risk awareness
- does not focus on risk awareness

**Criterion 3: Uncertainty Awareness**

+ focus on uncertainty awareness
- does not focus on uncertainty awareness

The processes and methods that will be reviewed are:

- Quality Function Deployment (QFD)
- Failure Mode and Effect Analysis (FMEA)
- Accelerated Life Testing (ALT)
- Degradation data and models (DDM)

- Load-strength concept
- Stressor-susceptibility concept
- Robust design – The Taguchi methodology
- Design for Six Sigma (DfSS)
- Reliability and Quality Matrix (RQM)

### Quality Function Deployment (QFD)

QFD is an overall concept that provides a means of translating customer requirements into the appropriate technical requirements for each stage of product development and production [Sullivan, 1986; Hauser and Clausing, 1988]. In this way the risk of developing a product that does not match the customer's requirements is reduced.

Traditionally the QFD approach has been used as a method for defining new products (RNIs), as well as for improving existing products (derivatives) [Zhao, et al., 2003]. The translation of customer requirements into design parameters is more critical for RNI products [De Toni, et al., 1998] as there is the less knowledge about the customer requirements.

However, QFD is least suitable for these kinds of products as the customer is not sure about his exact requirements yet. The customer has to think about a product that he has never seen or heard of before; the customer has no clear specification of the product. Or as [Deming, 1986] states "….the customer is not in a good position to prescribe the product or service that will help him in the future". In other words, there is uncertainty in the customer requirements, which QFD does not take in consideration. This might lead to the development of a product that does not fulfil the real customer wishes [Schmidt, 1997].

➔ summarising, QFD is proactive, risk focused but not uncertainty focused.

### ii. Failure Mode and Effect Analysis (FMEA)

FMEA is a technique for proactively evaluating product reliability [Cooper,2001; Fine, 1998; Smith 1999]. The FMEA considers the possible failure modes, the effects and the causes that lead to the product breakdown, and if it is due to materials or processes [De Toni, et al., 1998].

It is a technique to analyse design functions, potential failure modes, and effects of failure very early in the PDP during the predictive phase. When these are known, the focus then is to design out the failure modes wherever and whenever feasible as early as possible so that they do not reach the customer. In the case that potential failure modes cannot be prevented, corrective measures have to be taken.

First the potential failures are identified (step B&D). After that each potential risk element is quantified by judging its severity, probability of occurrence and solvability. This results in a risk priority number (RPN) (step E). Subsequently the highlighting can take place in the FMEA format by ordering these failures on importance according to the RPN.

Both the identification and quantification are assumed to be correct by FMEA, that is uncertainty management is completely overlooked by FMEA [Lu, 2002] making it unsuitable for RNI that are characterised by a high degree of uncertainty.

➔ summarising, FMEA is proactive, risk focused but not uncertainty focused.

**iii. Accelerated Life Testing (ALT)**

Lifetime data about a product's reliability can be obtained out of the field or through testing. For highly reliable products, which are designed to operate without failures for many years, it is quite difficult to estimate the time-to-failure distribution. Especially with the current TTM pressure there simply is no time to execute time-consuming tests. Fortunately, a number of acceleration methods is available that can overcome this conflicting situation [Lewis, 1996]. In ALT's, products are tested at an advanced stress level (such as temperature, voltage) or an increased frequency (compressed-time testing) and the results are extrapolated to estimate the product life under normal operating conditions [Lewis, 1996]. Accelerated life tests (ALT) are useful in identifying potential failure modes of products at the design stage in the predictive phase, before they are put to use in practical situations or environments [Jayatilleka and Okogbaa, 2001]. Essential is the choice of the stress profile used. Two generic variants can be identified:

### 1. ALT-generic list

Classical ALT strategies are mainly based on generic lists of failure mechanisms and have only limited relation with the actual failure rate curve of the products. This is a major pitfall in the use of these ALT's [Meeker and Escobar, 1998]. This generic list thus does not include type 1 uncertainties. [Lu, et al., 2000] states that current ALT practice in the consumer electronics industry is far from perfect if they use generic lists. This results in testing of irrelevant failure mechanisms under irrelevant stress profiles. The generated test results may then be misused to predict the product field performance. Businesses that have a strong need for a short TTM cannot accept this kind of practices but they simply do not have time to re-do their predictions.

### 2. ALT-physics of failure

An alternative to the classical ALT strategy that arises naturally is to test the product against the failure mechanisms identified from the analysis of the physics of the field failures. This strategy is termed Physics of Failure [Lu, et al., 2000]. This ALT are more suitable for the highly innovative consumer industry where less of the irrelevant tests are executed and time and money are saved [Lu, et al., 2000].

ALT is executed to gain knowledge about the lifetime distribution of a product under certain stress profiles simultaneously reducing type 2 uncertainty (step C) and quantifying failure risk (step E). However, ALT can only be performed effectively when the stress profiles that are used, correctly represent the relevant failure mechanisms. This is what ‘physics of failure’ based ALT aims for. However, in IPDP no field data is available as a brand new product is being developed; there is no information about relevant failure mechanisms (high type 1 uncertainty). ALT cannot deal with such uncertain input information as they do not include an uncertainty parameter.

➔ summarising, ALT is proactive, risk focused but not uncertainty focused

### iv. Degradation Data and Models (DDM)

Highly reliable products with few, or even zero, failures during life or in a reasonable testing period, make prediction and optimisation of reliability with traditional time-to-failure data very difficult. If failure can be defined in terms of a specified level of degradation during the predictive phase, then collecting degradation data can provide important information about a product’s reliability [Hoorn, 2003]. Compared to ALTs, in Degradation Data and Models the available testing time can be used more efficiently by monitoring and recording the actual product performance degradation over time. This degradation data is more informative for design and reliability engineers than just the times to failure [Crk, 2000; Petkova, 2003; Meeker and Escobar, 1998]. Besides the test time can be significantly shorter than if the times to failure are recorded [Crk, 2000] and less test items are needed [Lewis, 1996].

DDM’s have the same deficits as ALT’s, just as with ALTs, availability of information about the relevant failure mechanisms is a prerequisite for this method. As this information is not available for RNI products the DDM method is unsuitable for this kind of products. Degradation Data and Models focus on both type 2 uncertainty reduction (step C) and risk quantification (step E) management just like ALTs.

➔ summarising, DDM is proactive, risk focused but not uncertainty focused

### v. Load-strength Concept

This concept is based on the energy storage in a component to explain failures in a component as described by [Jensen, 1995]. The concept is based on the fact that components store energy when a load is applied. The component will fail when the limit of energy storage is reached.

Components will contain a variety of flaws and the strength will be distributed around a mean value. Similarly loads too will often have a range of values and can thus be described by a statistical distribution. Combining these two distributions it is possible to determine the failure probability.

The load-strength concept focuses on true physical failure indication (PRM step 5) as it tries to analyse when the physics of failure will happen by combining the load and strength distributions. This can only be modelled effectively in the predictive phase if the relevant failure mechanisms are known, i.e. when type 1 uncertainty is low. Besides enough information has to be available so that stress (load) and strength models can be developed (low type 2 uncertainty). This is an invalid assumption for RNI development projects which makes the method unsuitable for these products. The load-strength concept can explain failures in components or parts. However, [Brombacher, 1996], [Blanks, 1998] and [Bradley, 1999] have shown that current product reliability is less focused on components reliability.

➔ summarising, load-strength concept is proactive, risk focused but not uncertainty focused

### vi. Stressor-susceptibility concept

Although (mathematically) quite similar to the load-strength concept there are some differences [Lu, et al., 2000] which make the method more adequate for the high-volume consumer electronics industry:

Stressor-susceptibility analysis uses four different phases instead of three phases to describe the failure rate or hazard rate curve of products; thus uses the roller-coaster curve instead of the bathtub curve.

Stressor-susceptibility concentrates strongly on the behaviour of (weak, extreme) sub-populations within a large batch of products; meaning phase 1 and 2 failures of the roller-coaster curve.

[Brombacher, 1992] states that stressor/susceptibility models are usable for analysis of reliability problems. If the stressor-susceptibility analysis is fed with reliable information and the relevant failure mechanisms are known, effective predictions can be made about the probability of failure of certain stressor-susceptibility combinations even at the predictive phase of the PDP. However, in IPDP this information availability assumption is most often not satisfied due to high degree of uncertainty. The method thus focuses on step B&E and ignores uncertainty awareness management. Drawbacks of the stressor-susceptibility method are its mathematical complexity and its component focus.

➔ summarising, stressor/susceptibility models is proactive, risk focused but not uncertainty focused

**vii. Robust design, the Taguchi methodology**

The fundamental principle of Robust Design is to improve the quality of a product by minimising the effect of the causes of variation without eliminating the causes [Phadke, 1989]. A robust design may be defined as one for which the performance characteristics are very insensitive to variations in the manufacturing process, variability in environmental operation conditions, and deterioration with age. Taguchi's end goal is to optimize simultaneously the design of the product and the associated process [Ahmed, 1996].

Taguchi uses among other methods the Design of Experiments (DOE) to achieve a robust design. Originally a purely statistical method, Taguchi introduced DOE in the engineering field by applying it on product and process development [Fowlkes and Creveling, 1995]. It is a major method used in the robust design process at the predictive phase. Using the DOE, the physical and operative parameters which most influence a characteristic of performance of the product, can be determined [Wang et al., 1992]. Experiments are designed to optimise the product parameters that influence the final product quality.

Taguchi's method focuses on risk reduction (step E). It can improve product reliability when the relevant failure mechanisms and their risk quantities are known. Otherwise irrelevant product characteristics are made robust. This is a very big risk for IPDP making it an unsuitable method for those products.

➔ summarising, Taguchi Methodology is proactive, risk focused but not uncertainty focused

**viii. Design for Six Sigma (DfSS)**

Design for Six Sigma (DfSS) is an approach to design high quality products that covers the entire product development process and combines structured ways of working with rigorous project management [Creveling et. Al, 2003]. The approach starts in the predictive phase with identifying the consumer needs, translating these to critical to quality (CTQ) parameters, managing these parameters through design optimization. The main aim is to design products and processes that are less affected by variations. It is able to reduce risks based on information that is certain and hence does not focus uncertainty reduction when there is no prior information.

➔ summarising, DfSS is proactive, risk focused but not uncertainty focused

### Reliability and Quality Matrix (RQM)

RQM was developed as an enhancement of FMEA and QFD with the addition of an uncertainty parameter. If the quality of the input information is very good, RQM then presents only the results of FMEA and QFD. However, if there is uncertainty in the input information, RQM can act as an uncertainty management method to strengthen the weaknesses of FMEA and QFD when dealing with uncertain information [Lu, 2002a]. The advantage of RQM, compared to FMEA and QFD, is that it includes an uncertainty parameter and prioritises uncertainty management above risk management.

RQM decomposes the total project risks/uncertainties in product parts and processes. The failure mechanism identification (step A) process then only consists of defining all the parts and processes needed to manufacture the product. For these parts and processes both type 1 and 2 uncertainty indications (step B&C) and risk quantifications (step D&E) are required by RQM. Besides, the QFD part of RQM identifies the most important customer requirements and makes sure that the customer's requirements are reflected in the design specifications.

This method seems very promising as it covers the entire uncertainty and risk awareness management process. Because of this coverage this is the only method for which the known quantified risks are identified.

➔ summarising, RQM Method is proactive, risk focused and uncertainty focused

### Results

In figure 2.4 an overview is given of each of the above method's focus in the reliability management process. RQM is the only method that covers all uncertainty and risk awareness management steps.

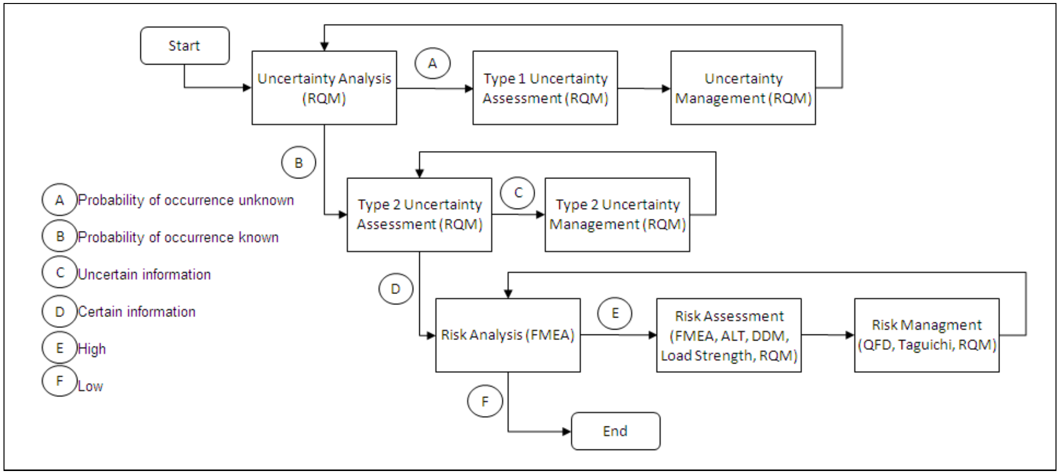


*Figure E1: Mapping of the risk and uncertainty management approaches to the reliability management*

The results of the review against the defined criteria are presented in table E1 below. The overview shows that the RQM Method is the only method that has a focus on the uncertainty management aspect in addition to the risk management aspect. Based on the two overviews (Figure E1 and Table E1), it can be concluded that the RQM method is the most promising method for proactive uncertainty and risk management.

| | Evaluation Criteria | | |
|---|---|---|---|
| | **Proactive** | **Risk Focus** | **Uncertainty Focus** |
| Methods reviewed | | | |
| Quality Function Deployment (QFD) | + | + | - |
| Failure Mode and Effect Analysis (FMEA) | + | + | - |
| Accelerated Life Testing (ALT) | + | + | - |
| Degradation data and models (DDM) | + | + | - |
| Load-strength concept | + | + | - |
| Stressor-susceptibility concept | + | + | - |
| Robust design - The Taguchi methodology | + | + | - |
| Design for Six Sigma (DfSS) | + | + | - |
| Reliability and Quality Matrix (RQM) | + | + | + |

*Table E1: Overview of reliability methods against the evaluation criteria*

## E.2. Conclusions

This appendix elaborated on the steps of the generic proactive reliability (risk and uncertainty) management process as depicted in figure 2.4.

## Appendix F: (In)Effective Type 2 Uncertainty Management Measurement Approach

This appendix will explain how effective and ineffective type 2 uncertainty management will be measured in the case analysis of chapter 3. Criterion will be identified that can be used to judge if RQM is capable of 'effective type 2 uncertainty management'.

The symbols used are explained in section F1. In section F2, the effective type 2 uncertainty management is focused while the ineffective type 2 uncertainty management is focused on in section F3. In section F4 the consequences for using risk data to measure RQM's type 2 uncertainty management (in)effectiveness are explained. Simplifications in the notations are made in section F5 and conclusions are finally drawn in section F6.

### F.1. Definition of Symbols

As there are many symbols used, the exact meaning and purpose as intended in this research thesis is defined below

$\hat{x}_{a_{it}}$ The predicted number of product failures per 100 products due to the predicted failure mechanism $a_i$ at time t in the predictive phase

$x_{a_i}$ The predicted number of product failure per 100 products due to the predicted failure mechanism $a_i$ when there is no uncertainty.

$d_t$ The difference between the $\hat{x}_{a_{it}}$ and the $x_{a_i}$ , if present at time t, caused by uncertainty in the $\hat{x}_{a_{it}}$ .

$y_{b_j}$ The verified number of product failures per 100 products due to verified failure mechanism $b_j$.

$A_t = \{a_{1t}, a_{2t}, \ldots.., a_{nt}\}$

$B = \{b_1, b_2, \ldots.., b_m\}$

The data is only considered if the failure mechanisms are known in the predictive and/or the verification phase (no type 1 uncertainty), i.e. the failure mechanisms E that satisfy: $E \in A_t$ and $E \in B$ for every t.

## F.2. Effective type 2 uncertainty management with RQM

Two generic scenarios are possible for an effectively managed type 2 uncertainty approach: High and Low initial uncertainty.

### F.2.1. High initial uncertainty

Effective type 2 uncertainty is only possible when RQM is used proactively. Only by using RQM in several iterations is it possible to predict, reduce and verify the type 2 uncertainty. This appendix uses a three phased prediction approach that the project team has applied, for illustrative purposes. Therefore t=3.

Effective type 2 uncertainty management for an initial high uncertainty example with t=3 has been illustrated in figure F1.

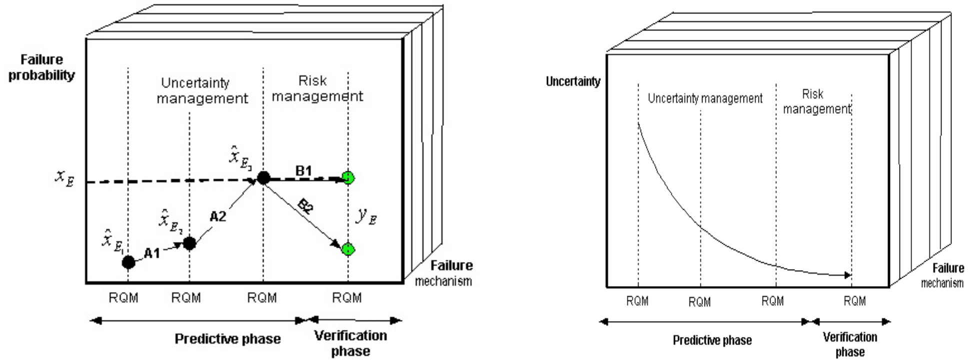


*Figure F1: The high initial type 2 uncertainty (right) makes that an iterative approach is required in the early phases to reduce uncertainty (A1 and A2 left). Subsequently effective risk management is possible (B1 or B2 left)*

During the predictive phase where high type 2 uncertainty exists, the early phases of the PDP (the time between the first, second and third RQM session in the example of figure F1) are used to manage the uncertainty. Management then means: prediction, reduction and verification. This iterative uncertainty management approach ensures that the uncertainty decreases and the $\hat{x}_{E_t}$ gradually comes closer to the $x_E$ . This approach of reducing uncertainty proactively along the PDP is visualised in the right part of figure F1.

When the type 2 uncertainty is very low (at t=3 just before the design is frozen) the $\hat{x}_{E_3} = x_E$ and the risk of failure mechanism E can then be managed correctly. The B1 and B2 arrows in the left part of figure F1 respectively show a scenario were the risk is accepted (no risk reduction and thus $\hat{x}_{E_3} = x_E = y_E$ )) and one were the risk is not accepted and therefore reduced ( $\hat{x}_{E_3} = x_E < y_E$ ).

The earlier the $\hat{x}_{E_t} = x_E$ the earlier one can adequately manage risks (as there is no uncertainty).

F.2.2. Initial low uncertainty

This scenario is much simpler as uncertainty does not need to be managed actively due to its initial low value. Right at the start of the project, called t=1, the $\hat{x}_{E_1} \approx x_E$ . Risk management can be initiated effectively from the start of the project. The risk can be reduced earlier in the project. This is visualised in figure F2.

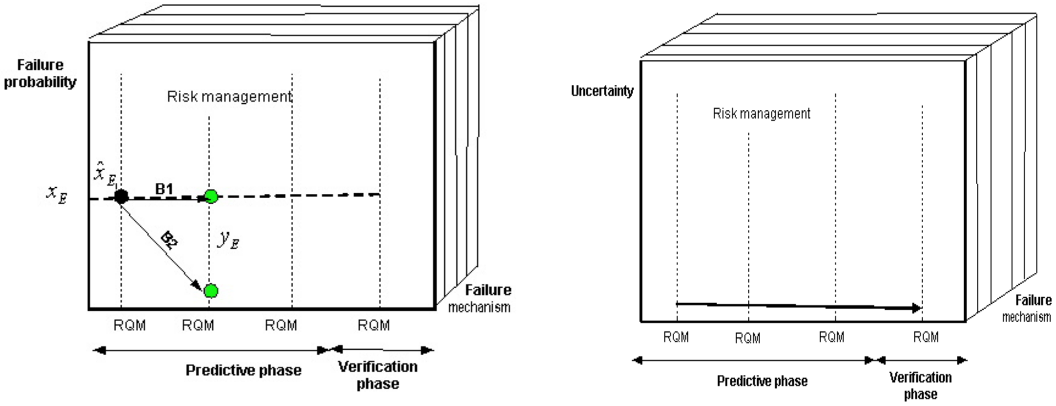


*Figure F2: The low initial type 2 uncertainty (right) makes that risks can be managed effectively early in the project (left).*

### F.3. Ineffective type 2 uncertainty management with RQM

In the scenario where an ineffectively managed type 2 uncertainty occurs, only initial high uncertainty will have undesirable consequences. If the initial uncertainty is low, risk management will not be deteriorated by the lack of adequate uncertainty management simply because uncertainty does not need to be managed.

If the type 2 uncertainty has been managed ineffectively with RQM there still is uncertainty present in the last risk prediction just before the design is frozen. Then the $\hat{x}_{E_3}$ and the $x_E$ show a significant difference. This difference can be due to an overestimation $\hat{x}_{E_3} > x_E$ or due to an underestimation $\hat{x}_{E_3} < x_E$ . Risk management (reduction) measures must then be initiated based on these under- or overestimation.

Both the type 2 uncertainty and eventual risk reduction measures have to be considered to explain the difference between the last risk prediction $\hat{x}_{E_3}$ and the verified risk $y_E$ . This is visualised in figure F3 below.

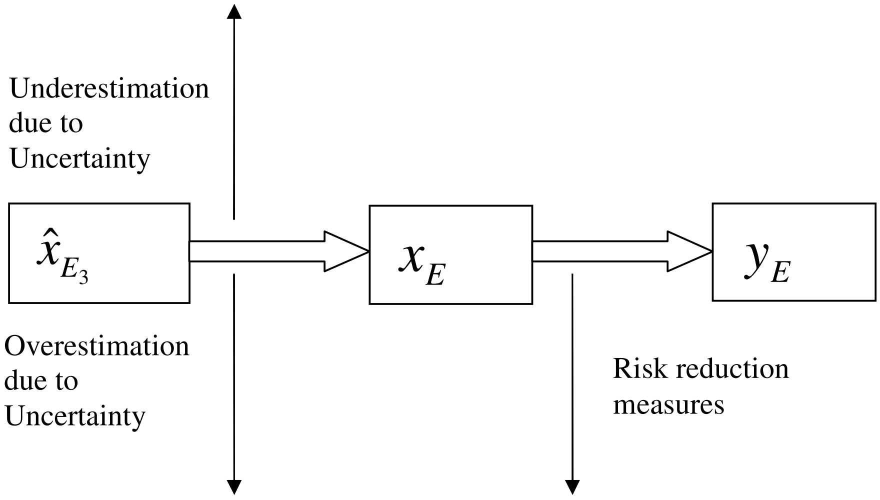
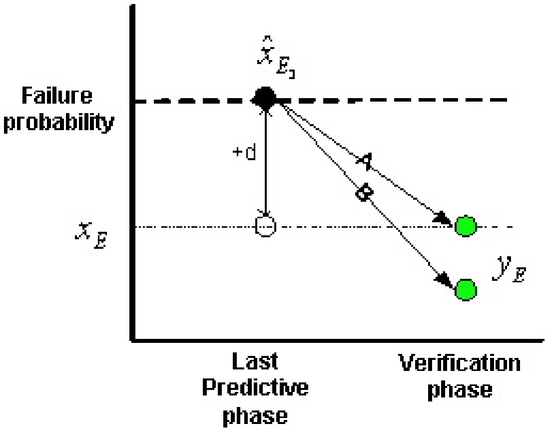


*Figure F3: Forces that explain the difference between the last risk prediction and the verified risk in the case that type 2 uncertainty is present in the* $\hat{x}_{E_3}$

As the risk in the last estimation can be over- or underestimated due to the uncertainty present two uncertainty arrows are depicted in figure F3. The under- and overestimated risk scenarios are further elaborated below.

### F.3.1. Risk overestimation ( $\hat{x}_{E_3} > x_E$ )

The uncertainty in this scenario reflects a situation where the risk is overestimated with an amount d that is equal to $\hat{x}_{E_3}$ minus $x_E$ . This is illustrated in figure F4 below.



A Uncertainty reduced but no risk reduction

B Risk reduced due to uncertainty reduction and risk reduction

*Figure F4: Risk overestimation in the last predictive phase due to ineffectively managed type 2 uncertainty.*

When the risk is overestimated only risk decreases will be observed as the reduced uncertainty in the verification phase and eventual risk reduction activities initiated in the last predictive phase both lower the risk.

In case A of figure F4 no risk reduction activities are initiated and the observed risk decrease is completely due to decreased uncertainty.

In case B both uncertainty decreases and risk reduction activities result in lower observed risk compared to the last predicted risk.

### F.3.2. Risk underestimation: ( $\hat{x}_{E_3} < x_E$ )

In this situation a risk increase $y_E > \hat{x}_{E_3}$ is observed when the risk increase due to reduced uncertainty is stronger than the risk decrease due to deliberate risk reduction activities. Process C and D in figure F5 illustrate this reasoning.

In an observed risk that stays the same $y_E = \hat{x}_{E_3}$ or decreases $y_E < \hat{x}_{E_3}$ the risk reduction measures respectively equal or dominate the risk increase due to the decline in uncertainty. In spite of the fact that one observes a lower risk in the verification phase than predicted, which is desirable, uncertainty has not been managed effectively. The extensive risk reduction measures overshadow the unidentified uncertainty, thus there is inadequate uncertainty management of RQM. This is depicted by arrow E and F in figure F5.

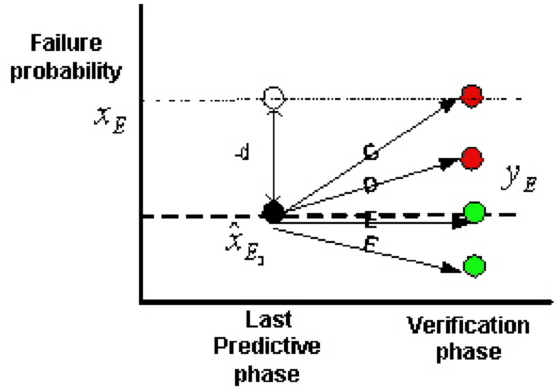


*Figure F5: Risk underestimation in the last predictive phase due to ineffectively managed type 2 uncertainty*

### D.4. Consequences for using risk data as indicator for (in)effective uncertainty management

The previous scenario analysis revealed that a risk increase in a known failure mechanism E is due to ineffectively managed type 2 uncertainty. This can only be observed in the case of an underestimation (C and D in figure F5). However, a risk that stays level or decreases does not necessarily mean that the type 2 uncertainty has been managed effectively. This can be the case in both under- and overestimation situations (A and B in figure F4, E and F in figure F5). Theoretically it therefore is possible to find no risk increases in spite of the fact that the type 2 uncertainty has been managed ineffectively.

Thus to measure RQM's type 2 uncertainty management (in)effectiveness, risk data cannot unambiguously reveal all (in)effectively managed uncertainties. However, two observations will justify a focus on risk data, and risk increases in particular:

> Risk predictions under uncertainty will in practice quite often lead to risk underestimation. This is due to the fact that a risk will only be considered significant when one has concrete evidence. However, under uncertainty one is unsure and has no clear evidence about the risk and will therefore consider it as low risk. The same observation was made by [Lu, 2002] when implementing RQM. Thus, there will less overestimations compared to underestimations.
>
> Risk overestimations, on the other hand, are not very threatening for the product reliability (from a risk management perspective) as both the uncertainty decrease and possible risk reduction activities make that the true risk in the industrialization phase of the PDP is lower than the predicted risk. In other words: a risk overestimation causes one to err on the conservative side with respect to product reliability, which results in the initiation of risk reduction measures that, together with the risk decrease due to the uncertainty decline, result in a low verified risk value.

These two observations (overestimations will occur less frequently compared to underestimations and overestimations will result in less severe risks) imply that it is very likely that a risk increase is observed when a type 2 uncertainty has been managed ineffectively. A focus on risk increases, as a metric for ineffectively managed type 2 uncertainty, is therefore justified. Identifying the number and amount of risk increases for all known failure mechanisms will indicate RQM’s type 2 uncertainty management (in)effectiveness.

When a certain failure mechanism shows an increased verified risk compared to the previous risk predictions, RQM has ineffectively managed type 2 uncertainty. Summing the risk increase for all failure mechanisms that show such an increased risk value will indicate the ineffectiveness of RQM for type 2 uncertainty management.

Thus for a single known failure mechanism E ($E \in A_{last}$ , $E \in B$)

$y_E > \hat{x}_{E_{last}}$ RQM ineffectively manages type 2 uncertainties

$y_E \leq \hat{x}_{E_{last}}$ This is the desired situation and is considered effectively managed type 2 uncertainty.

The amount of risk not predicted due to ineffectively managed type 2 uncertainty then is the increased failure probability sum of all failure mechanisms E which are element of both data sets A$_{last}$ and B and that satisfy $y_E > \hat{x}_{E_{last}}$. This is equal to:

$$\sum_{E \in A, B \wedge y_E > \hat{x}_{E_{last}}} (y_E - \hat{x}_{E_{last}})$$

### F.5. Simplified Notation

In the above sections, it has been shown that an evaluation of RQM's type 2 uncertainty management (in)effectiveness is possible with risk data. The last risk prediction ( $\hat{x}_{E_{last}}$ ) and verified risk ( $y_E$ ) for the known failure mechanisms E then have to be compared. As this comparison will be restricted to this last predictive and the verified phase the time variable t can be omitted. The simplified notation that will be used in the rest of this thesis is as follows. The predicted risk for failure mechanism E ( $\hat{x}_E$ ) represents the predicted risk for failure mechanism E at the last risk prediction ( $\hat{x}_{E_{last}}$ )

### F.6. Conclusion

This appendix has shown that RQM's type 2 uncertainty management (in)effectiveness can be measured with risk data. Despite the fact that every risk increase observed indicates an ineffectively managed uncertainty, not every risk decrease indicates an effectively managed type 2 uncertainty. However, it is shown that looking at the amount and size of the risk increases one can come to a very valid approximation of the type 2 uncertainty management (in)effectiveness of RQM. This will therefore be the approach and focus of the type 2 management (in)effectiveness analysis.